

**STUDY ON MECHANICAL BEHAVIOR OF FROZEN SOILS SUBJECTED TO
CYCLIC FREEZING-THAWING PROCESS**

A Thesis

by

BOHAN ZHOU

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Chair of Committee,	Marcelo Sanchez
Committee Members,	Charles Aubeny
	Eduardo Gildin
Head of Department,	Robin Autenrieth

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ABSTRACT

The behavior of frozen soil has drawn significant attention in recent years, particularly its response when subjected to cyclic freezing-thawing. This interest is not only driven by practical geotechnical engineering problems (e.g. distress of foundations due to thawing, cracking of the super structure, and differential movements in roads and other infrastructures), but also by the important role that frozen grounds play in energy challenges and waste containments problems nowadays. The mechanical behavior of frozen soils under freezing-thawing cycles is not very well understood yet and the existent models are also quite limited to explain the complex response of this material. This thesis conducts cyclic freezing-thawing laboratory tests with a kind of silt in an open system under different mechanical conditions and controlled environment, and then uses Matlab software to simulate the test results and model the volumetric behavior employing the use of corresponding formulations. A better understanding on the behavior of soils subjected to freezing-thawing cycles has been gained in this research. A new set of high quality experimental data of cyclic freezing-thawing soils under different loading conditions and different cyclic freezing-thawing history has been obtained, and a preliminary mechanical model accounting for the effect of freezing–thawing cycles on volume changes of frozen soils is developed.

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Contributors

Part 1, faculty committee recognition

This work was supervised by a thesis committee consisting of Professor Marcelo Sanchez and Charles Aubeny of the Department of Civil Engineering and Professor Eduardo Gildin of the Department of Petroleum Engineering.

Part 2, student/collaborator contributions

The cyclic freezing-thawing lab tests introduced in Section 3 was conducted with the help of Mr. Juyoung Lee.

All other work conducted for the thesis was completed by the student independently.

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1 INTRODUCTION

1.1 Background

Frozen soils are soils subjected to freezing process, in which phase change from water to ice will happen. Frozen ground can be divided into seasonally frozen ground, intermittently frozen ground, and permafrost ground. In seasonally frozen ground, soil is frozen for 15 days or more per year, while in intermittently frozen ground, soil is frozen for fewer than 15 days per year. Permafrost ground occupies about 22.79 million km² or 23.9% of the exposed land surface, while on average, the maximum extent of seasonally frozen ground is about 55 million km² or 55% of the total land area. The frozen ground distribution is shown in Figure 1.1.



Figure 1.1 Distribution of Frozen Ground (Rekacewicz, 2005)

As a result of their wide distribution, frozen soils are closely connected to our life, and problems resulted from frozen soils, especially soils subjected to cyclic freezing-thawing process are becoming more significant constraints in many fields (i.e. engineering construction, waste disposal and energy exploitation). In order to well understand the behavior of frozen, and solve problems encountered in practical engineering problems, many researcher have made their attempts, not only in experimental tests but also in modeling work.

For the experimental campaign, some laboratory tests have been conducted to study the volumetric and shearing behavior of frozen soils. From them it has been possible to estimate the changes in pre-consolidation pressure, stiffness, shear strength and also permeability associated with different subzero temperatures (e.g. Lee et al., 2002 and Qi et al., 2010). Some studies focused on the effect of freezing-thawing cycles on properties of clays and silts, like elastic modulus, cohesion, friction angle, shear strength, and hydraulic conductivity. They conducted cyclic tests with open and/or close system, but never provide a reliable model for the mechanical behavior of cyclic freezing-thawing soil (e.g. Jilin Qi et al., 2008 and Dayan Wang et al., 2007).

Different types of models have been proposed for the modeling of frozen soil behavior. For example, Thomas et al., (2009) considered an elastic model coupled with the thermo-hydraulic problems. Nishimura et al., (2009) firstly extended the Barcelona Basic model (BBM) for unsaturated soils (Alonso et al., 1990) to simulate the behavior of frozen soils qualitatively without a validation against experimental mechanical test.

Actually, current study on frozen soil behavior, particularly frozen soils subjected to cyclic freezing-thawing process, is still far from enough. Some gaps in current knowledge are not well filled yet.

1.2 Motivation

The interest on the mechanical behavior of frozen soils was initially driven (mainly) by problems associated with ground heave. Afterwards, the noticeable recent changes in climate worldwide have increased the interest in the study of frozen soils, especially in places where freezing-thawing process will accrue, like Canada and Russia. In addition, engineering properties of the soils such as strength, stiffness, coefficient of permeability, and mechanical behavior change drastically with changes in temperature and freezing-thawing cycles. These property changes give rise to many engineering practical problems, such as distress of foundations due to thawing, cracking of the super structures, and differential movements in roads and other infrastructures. These problems bring about financial losses and safety problems, and some are shown in Figure 1.2.



a)



b)

Figure 1.2 Practical Engineering Problems a) Building Failure due to Thaw Settlement (Romanovsky, 2010) b) Road Failure (Turchett, 2010)

Besides, frozen soils have low permeability, which is a good material to be used in dams and barriers for waste containment, as shown in Figure 1.3 below.



a)



b)

Figure 1.3 Applications of Frozen Soils a) Construction of a Frozen Core Dam (Turchett, 2010) b) Frozen Soil Barrier System at Oak Ridge National Laboratory (DOE, 1999)

Furthermore, with the discovery of fossil fuels in recent years, like petroleum and gas hydrates near the Arctic Circle as well as permafrost regions worldwide, frozen soils will become a topic of central interest, and to better understand their behavior will be key to enhance the exploitation of these energy resources.

Moreover, the modeling of cyclic freezing-thawing behavior of soils including the associated volume changes is a subject that has received little attention; however it is a critical feature to design engineering problems in grounds subjected to these conditions. All of these factors foster our motivation on the study of mechanical behavior of frozen soils subjected to cyclic freezing-thawing process.

1.3 Objectives and activities towards them

The underlying goal of this thesis is to gain a better understanding on the mechanical behavior of frozen soils, particularly on the mechanical behavior of soil subjected to cyclic freezing-thawing solicitations. Experimental, fundamental and numerical investigation has conducted to achieve this objective.

The goal of the experimental campaign is to produce a new set of high quality experimental data associated with the volume change of soils subjected to freezing-thawing cycles that would help to understand the behavior of soils under these complex conditions. The fundamental studies focus on the effect of unfrozen water on the mechanical behavior of soils and on how to incorporate the three phase condition of this type of soil (i.e. unfrozen water, solid and ice) in a consistent mathematical framework for frozen soils, The modeling activities have been focused on the developing a

constitutive model for soils subjected to freezing-thawing cycles and its validation against the experimental data generated in this project and also already published ones.

1.4 Methodology

As for the experimental campaign, the first step was the physical characterization of the soil adopted in this research. A kind of silt from U.S. Silica Company was chosen in this thesis. Routinely geotechnical tests were conducted to learn about the basic properties of this soil. Proctor and mechanical tests were also conducted to learn about the mechanical properties of this material. Slurry soil sample with a water content of 30% was chosen to perform tests for achieving the goal of fully saturated and evident test results. Cyclic freezing-thawing tests with a temperature range from -7°C to 5°C are conducted in a freezing Chamber, in which temperature values between positive and negative can be set and circulated. Devices with open system are designed and 3D printed for the purpose of allowing water moving in and out freely during freezing-thawing cycles. Normally consolidated loose soil samples with pre-consolidation pressure of 10kpa and 100kpa are tested under same load steps together with over consolidated dense soil samples with pre-consolidation pressure of 500kpa and 1250kpa, so as to obtain ample tests results under different mechanical conditions, also, these results can be compared more effectively and obviously. Test data will be measured by LVDT, and values as well as plots will be recorded and shown by LabVIEW program on the computer connected.

As for the modeling campaign, BBM concept, incorporating cryogenic suction and temperature, is extended to developing the preliminary mechanical model for frozen

soils subjected to cyclic freezing-thawing back on the experiment data gathered in the experimental campaign as well as on published results. Matlab is selected to help develop and modify the mechanical model, where plots (i.e. void ratio versus number of freezing-thawing cycles) can be drawn and compared with results obtained from lab experimental tests. Equations and formulas related are presented in the Appendix A.

1.5 Organization of the thesis

The first section is an introduction of this thesis, including basic background of the research topic, gaps existing in current knowledge on the topic, objectives and activities towards achieving them, and a methodology introduction on this research.

More background of frozen soils will be introduced explicitly in Section 2 based on some former research, including their porous media scope study, properties and mechanical behaviors.

In Section 3, the thesis will mainly introduce and summarize all the cyclic freezing-thawing tests that have been performed to support the research topic. The goal of the experimental campaign is to produce a new set of high quality experimental data associated with the volume change of soils subjected to freezing-thawing cycles that would help to understand the behavior of soils under these complex conditions.

Section 4 will focus on description of the preliminary mechanical model developed for soils subjected to freezing-thawing cycles and its validation against the experimental data generated in this project as well as already published ones.

The last section will summarize all the work has been down, and at the seam time, an outlook for future work will also be presented in this part.

2 MECHANICAL BEHAVIOR OF FROZEN SOILS

2.1 Introduction

In this part of the thesis, more background of frozen soils will be elaborated in detail. All the research work in this thesis on frozen soils will be completed in a porous media research scope. Ice and unfrozen water as well as their influence on soil properties will also be introduced. Besides, mechanical behaviors of frozen soils, such as volumetric behavior and shear behavior, will be illustrated by some former research achievements also.

2.2 Study of frozen soils in porous media scope

As research on some other kinds of soils, study of frozen soil is performed in the scope of porous media, where phases and species will be incorporated. Generally, the three phases we usually deal with are solid, liquid and gas, while the three species are mineral, water and air. Mineral is the solid phase; the liquid phase contains water and air dissolved, and gas phase contains mixture of dry air and water vapor. Water is considered as liquid as well as that evaporated in the gas phase, while air is considered as gas as well as that dissolved in the liquid phase. The schematic representation of phases and species in porous media in general are shown in Figure 2.1 below.

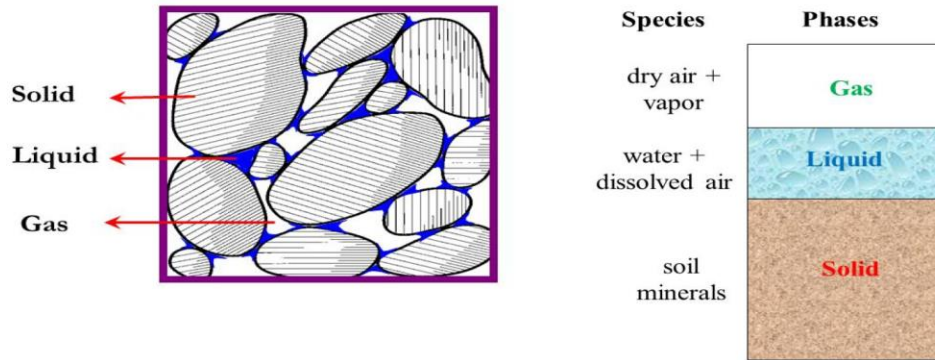


Figure 2.1 Schematic representations of phases and species in porous media

In this thesis, the soil we research on is fully saturated by water before freezing, which means there is no air. The only two phases before freezing are liquid and solid, and the two species are water and soil minerals. However, when the soil freezes, not all water will become ice, there is still amount of water remain unfrozen, which is called unfrozen water. The content of unfrozen water was first stated by Tice, et al., (1976). The amount of unfrozen water is affected by many factors, such as temperature, pressure, pore size, and soil types. So, when the fully saturated soil is frozen, the species existing will be water, soil minerals, and ice, while the phases existing will be liquid and solid. The phases and species in our research soil samples are shown in Figure 2.2 below.

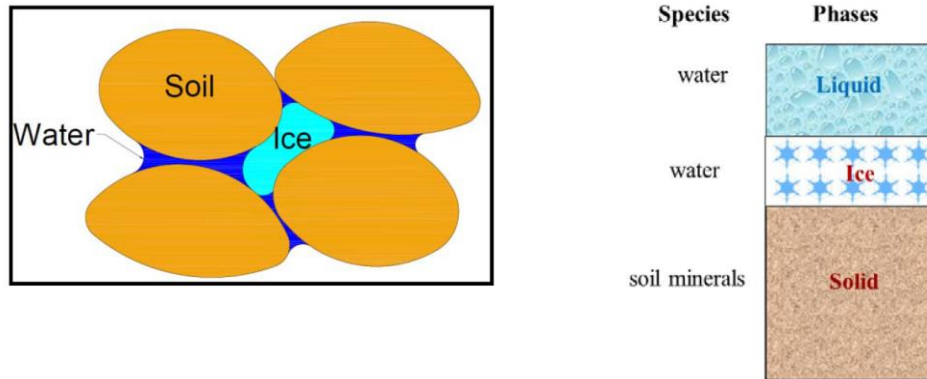


Figure 2.2 Schematic representations of phases and species in fully saturated frozen soil

In recent years, the study in porous media, such as soils and rocks, under complex and extreme conditions involving mechanical, thermal, hydraulic, chemical and biological coupled actions has received increased attention. Among these things, the THM-coupled phenomenon is a common one, which will also become a promising direction of frozen soils in porous media scope. Figure 2.3 shows the THM-coupled phenomenon and the mutual relations between them.

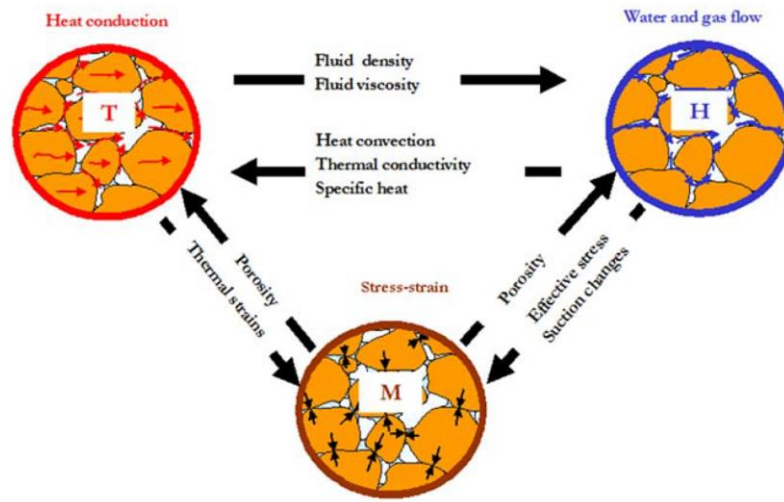


Figure 2.3 THM-coupled Phenomenon (Sanchez, 2010)

The thermal part includes heat conduction, heat advection, phase changes and so on; the hydraulic part contains liquid flow, gas flow, phase changes, vapor diffusion and so on, while the mechanical part consists of problem related to effective stress, suction, and temperature.

2.3 Ice and unfrozen water in frozen soils

2.3.1 Ice formation and properties

The important two parts we have to take care of in frozen soils are ice and unfrozen water, and study on these will help to make clear the mechanical behavior of frozen soils. As we all know, ice will form when temperature is below the freezing point, and the formation of ice depends on a number of factors, such as pressure, freezing temperature, pore size, and even the type of soils. For example, water in larger pores

Among the factors stated above, pressure and temperature are the two main factors influencing the formation of ice. With different pressures and temperatures, water will have different phase status, solid, liquid and air. Figure 2.4 gives details about the different types of ice in the Pressure-Temperature diagram by Hokanomono (2014).



From the figure above, we can also see the most predominant ice type found in soils in the biosphere is the type Ice 'I_h', which is generally formed between 1Pa and 1MPa in pressure, and from 0°C to –120°C in temperature. In the study, the thesis will only consider this ice type, for most of our practical engineering problems will happen in this pressure and temperature range.

The main differences between different ice formation types derive from c-axis direction. As shown in Figure 2.5 below, a) is Granular Ice; b) is Columnar-grained Ice; c) is a kind of a) with random c-axis orientation; d) is a kind of b) with horizontal c-axis.

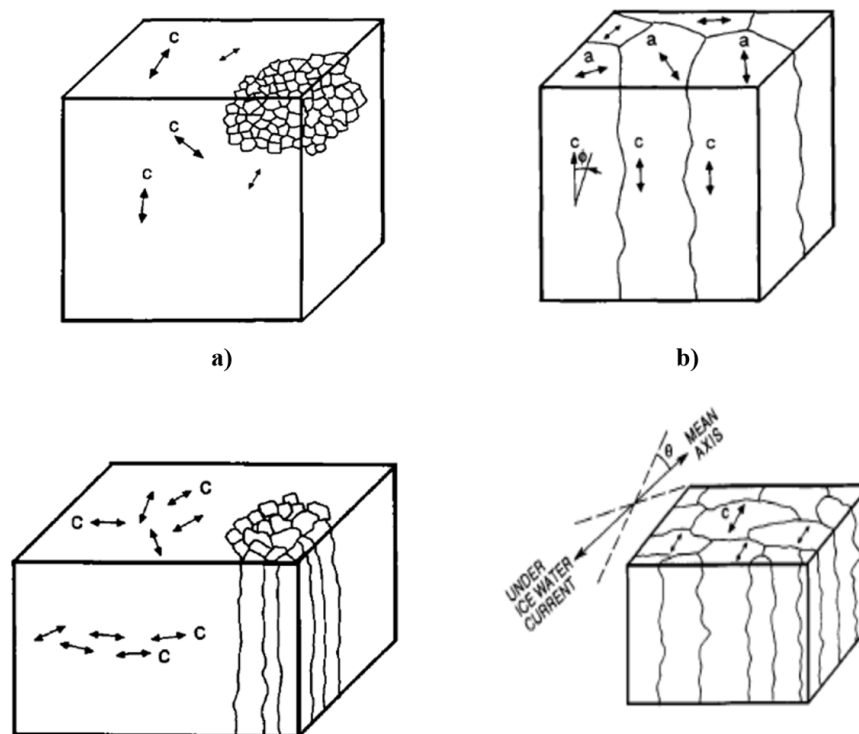


Figure 2.5 Different Ice Formation Type (Sinha 1989)

The existence of ice will change the mechanical properties of frozen soils for its properties such as stiffness, modulus, are different from water. Some researchers studied on the property change with different subzero temperatures (e.g. Sinha, 1989). The test results of Sinha are shown in Figure 2.6 below. It can be observed that the Young Modulus (E), shear modulus (G), and Poisson ration remain almost the same when temperatures changes from 0 to -50 °C. Conclusion can be drawn that the impact of freezing temperature on ice elastic properties is not very significant.

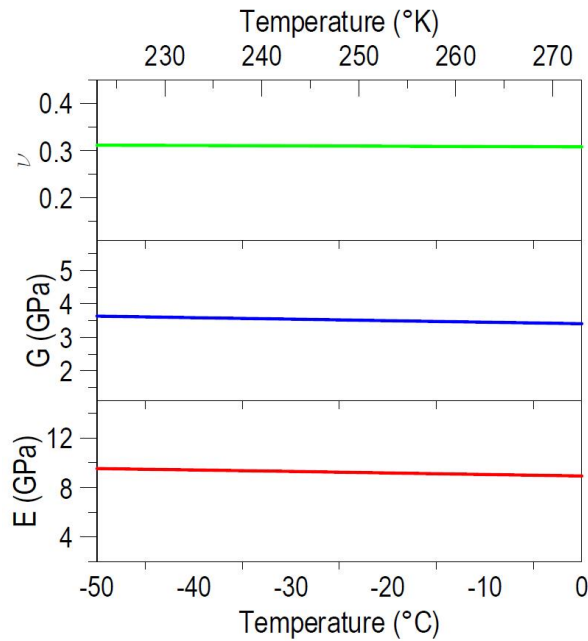


Figure 2.6 Freezing Temperatures on Ice Elastic Properties (Sinha, 1989)

2.3.2 Cryogenic suction in frozen soils

Compared to matric suction in unsaturated soil, which is the difference between air pressure and water pressure; there is also a kind of suction in saturated frozen soil,

which is called cryogenic suction, denoted by S_c . It is the difference between ice pressure and unfrozen water pressure, as shown in Eq. 2.1 below. We can consider air is replaced by ice when we develop the mechanical model in Section 4.

$$S_c = P_i - P_w \quad (2.1)$$

The relationship between degree of water saturation and degree of ice saturation is shown in Eq. 2.2 below.

$$S_i = 1 - S_w \quad (2.2)$$

For the purpose to obtain the value of degree of ice saturation, a formula related to temperature was stated by Tice et al., 1976 as shown in Eq. 2.3 below, where T is temperature, α is experimental parameter, and T_0 is the freezing temperature of pore water in Celsius temperature.

$$S_i = \begin{cases} 1 - [1 - (T - T_0)]^\alpha & T \leq T_0 \\ 0 & T > T_0 \end{cases} \quad (2.3)$$

The degree of ice saturation has an important effect on the volume behavior, for volume tends to expand when phase changes from water to ice; the difference in density causes the difference in volume. It has been estimated that volume expansion will be around 9 percent when water freezes to ice by Tice et al., (1988). Further cooling reduces the volume a little but negligibly small as shown in Figure 2.7 below. This will be illustrated in detail in Section 4 later.

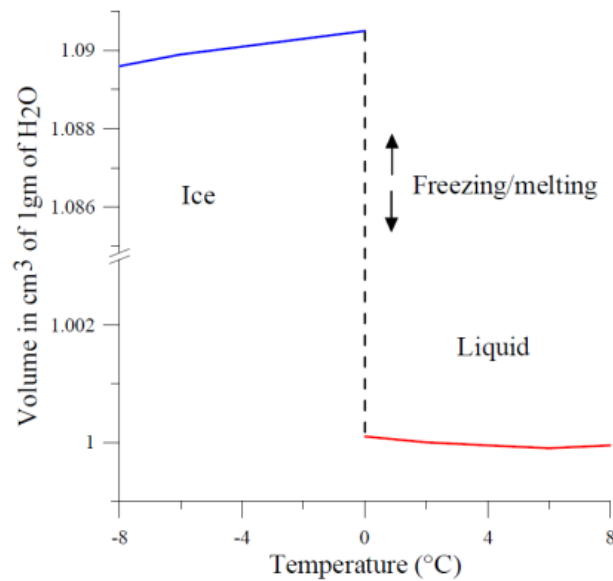


Figure 2.7 Water and Ice Phase Change (Tice et al., 1988)

2.4 Mechanical behavior of frozen soils

The importance of understanding the mechanical behavior of frozen soils is never overemphasized. It is the basic task when dealing with practical engineering problems. This part of the thesis will introduce the mechanical behavior of frozen soils by both former tests and existing models.

2.4.1 Volumetric and shear behavior of frozen soil

For achieving the goal of making clear of how frozen soils behave mechanically and how to model the mechanical behavior of frozen soils, some tests focusing on volumetric behavior and shear behavior of frozen soils were conducted. Lee et al. performed consolidation tests under different subzero temperatures with natural frozen soil samples in 2002 to research on the volumetric behavior, while Qi et al. performed

similar tests in 2010 with reconstituted frozen soil samples. Figure 2.8 below shows the results of volumetric behavior of frozen soil by the tests they performed.

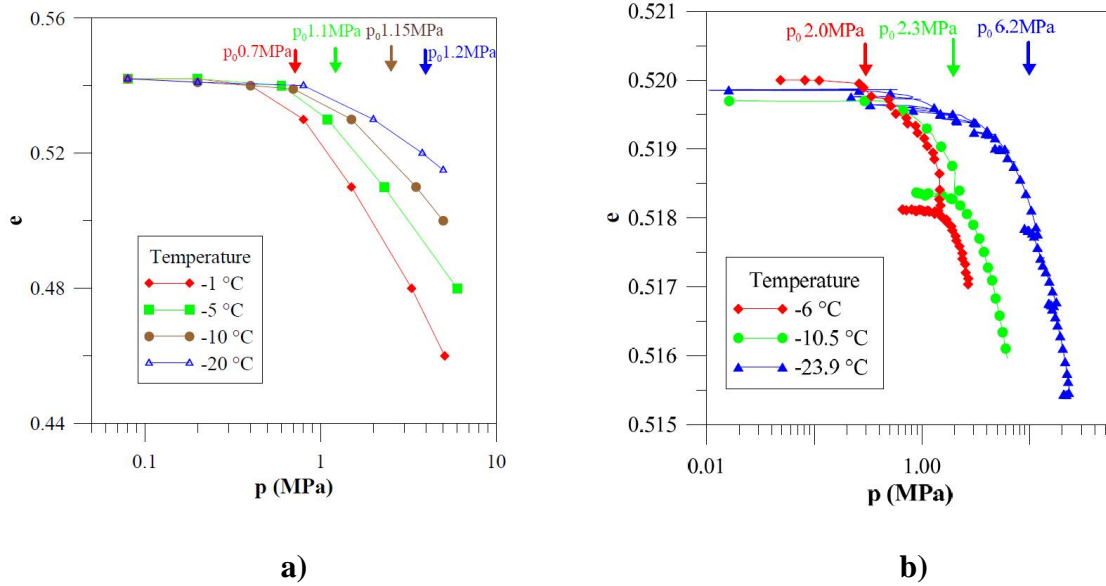


Figure 2.8 Volumetric Behavior of Frozen Soil: a) Reconstituted frozen samples (Lee et al., 2002) b) Natural frozen samples (Qi et al., 2010)

It can be observed from the figure above that the values of the pre-consolidation pressures tend to increase with the decrease of temperature. This is because the cryogenic suction increases the elastic domain of the soil sample. Also, we can conclude that elastic slope is not significantly affected by temperatures, but the virgin consolidation slope is affected by temperatures apparently, which is decreasing when temperature decreases. The entire phenomenon demonstrates that cryogenic suction, which increase with temperature increase the stiffness of frozen soils.

For the campaign of shear behavior study, a series of unconfined and tri-axial tests were also conducted by former researchers with soil samples shared by applying

increasing deviatoric loads. Figure 2.9 below shows the change of the deviatoric stress with strain for unconfined tri-axial test using reconstituted samples of frozen soil by Parmeswaran and Jones (1981). It can be observed that both the stiffness of the soil and the maximum deviatoric stress increases with the decrease of temperature, and this is because the lower the temperature is, the more ice will form, and the larger the cryogenic suction, which can increase stiffness and shear strength of soil, will form.

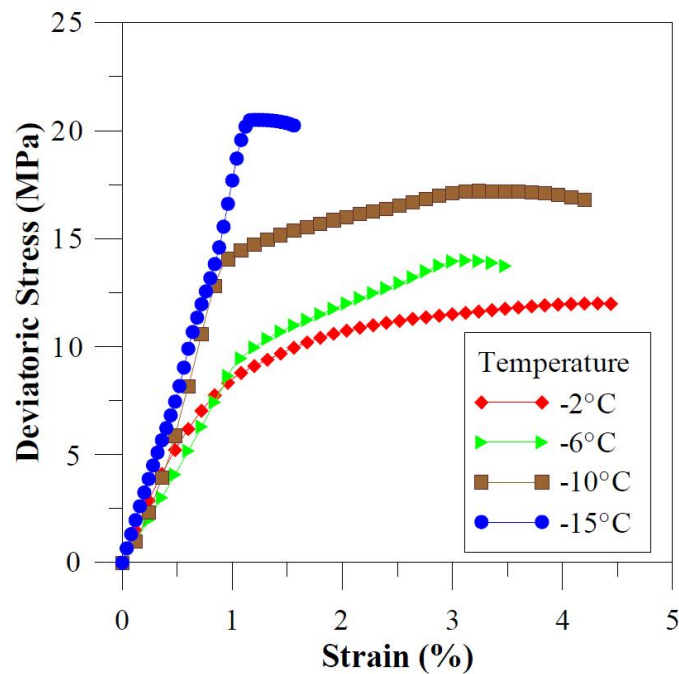


Figure 2.9 Change of Stress-strain Behavior with Temperature
(Parmeswaran and Jones 1981)

2.4.2 Existing models for frozen soils

The drive towards developing mechanical models for understanding behavior of frozen soils stems from design of foundations in frozen soils, and mechanical models together with some hydraulic (H) and/or temperature (T) coupled models were developed.

Mechanical constitutive models then started to be proposed which is a huge step forward, like Nixon, (1990). He proposed an uncoupled thermo-mechanical model. But lab test showed there is a direct relationship between mechanical and thermal behavior of frozen soil.

When soil research in micro scope became more popular, some frameworks model frozen soil in porous media scope, like Michalowski and Zhu, (2006), and they stated the ‘porosity rate function’ which was used to correlate the changes in freezing temperatures with the volumetric deformation. However, plastic mechanical part cannot be shown in this model.

Some other researchers, like Yusufuku and Springman, (2001). They considered the frozen soils as a material composed of granular ice matrix and soil particles, and the model is shown in Figure 2.10 below.

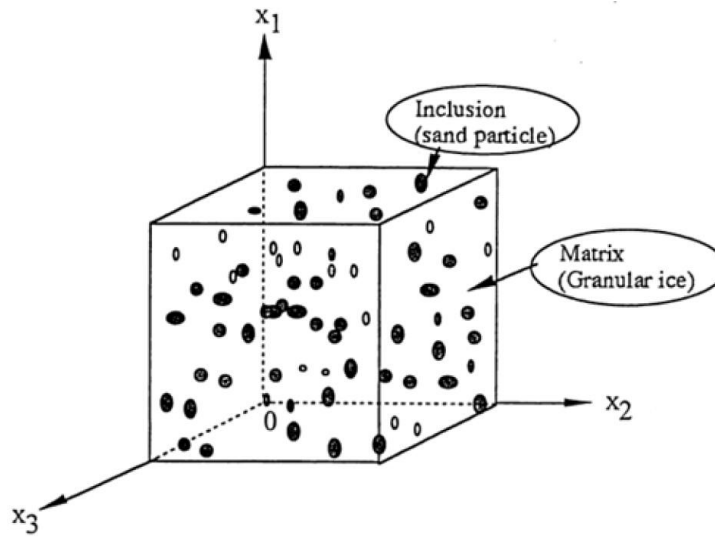


Figure 2.10 Schematic Review of the Composed Soil Structure (Yusufuku and Springman, 2001)

Thomas et al., (2009) considered an elastic mechanical model coupled to temperature-hydraulic (TH) model, although he considered mechanical together with hydraulic and thermal factors, but the plastic behavior cannot be modeled by his framework.

A new framework to model the behavior of frozen soils was proposed by Nishimura et al., (2009). They applied the Barcelona Basic Model (BBM) to simulate the mechanical behavior of frozen soils together with cryonic suction as an additional stress variable. BBM is Barcelona Basic Model for short, which is firstly stated by Gen, Alonso and Josa in 1990. It is an elasto-plastic model developed from Cam Clay Model, and it takes suction into consideration. The Cam Clay Model is for the condition where suction is equal to zero, which means soil is fully saturated, while BBM is for the condition where suction is not zero, which means soil is partly saturated. The two main

stress variables for BBM are net stress (total stress minus air pressure) and matric suction (excess of air pressure over the liquid pressure). As for frozen soil study, BBM is modified with new defined net stress σ_n and cryogenic S_c in Eq. 2.4.

$$\begin{aligned}\sigma_n &= \sigma - \max(P_i, P_l, 0) \\ S_c &= \max(P_i - P_l, 0)\end{aligned}\tag{2.4}$$

Where σ is the mean stress; σ_n is the net stress.

Modified BBM has become very popular in modeling unsaturated soils now, and many models for frozen soil are based on this, like Ajay Shastri, Marcelo Sanchez, (2012). They proposed a mechanical model of frozen soils incorporating the effect of cryogenic suction and temperature. But they are all lack of enough lab tests support. After people started to pay more attention to cyclic freezing-thawing behavior of frozen soils, some other coupled models for freezing and thawing soils were also proposed in recent years, like a thermal-mechanical constitutive modeling for freezing and thawing soil by Wei et al., (2011). They developed an elasto-plastic constitutive model developed from Cam Clay Model for freezing and thawing soils to capture the deformation behavior and strength evolution of the soil subjected to mechanical loading as well as temperature changes, however, cryogenic suction was not be analyzed in this model. This thesis will mainly focus on the mechanical study of frozen soils subjected to cyclic freezing-thawing process, and tests relevant and model development will be elaborate in detail in the following sections.

3 CYCLIC FREEZING-THAWING LAB TESTS OF FROZEN SOIL

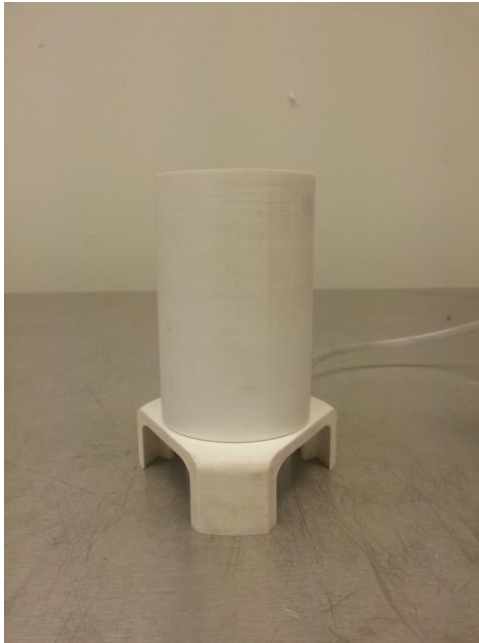
3.1 Introduction

The goal of the experimental campaign is to produce a new set of high quality experimental data associated with the volume change of soils subjected to freezing-thawing cycles that would help to understand the behavior of soils under these complex conditions. In this section, cyclic freezing-thawing tests will be introduced in an order of experimental setup, former tests background, test material choosing, test procedures, test results, and test summarization. All of these will be elaborated in the following parts.

3.2 Experimental setup and material

All the cyclic freezing-thawing tests are performed with the same equipment and device. For frozen soil tests, the device is generally either an open system or a closed system according to former tests on frozen soils. The device we use here is an open system, and is combined by three parts. One is the plastic mold (Figure 3.1 a) printed by 3D printer, and the inner part which contains the soil sample is 39mm in height and 39mm in diameter; a small metal cylinder with a thickness of 20 mm and diameter of 20 mm will be placed on the top of the sample. A plunger with a porous stone at the end of it is inserted into the mold, and gets touched to the top of the metal ring. Target surcharge load will be placed on the top of the plunger. The base pedestal (Figure 3.1 c) of the mold contains a porous stone for drainage, and the stone is connected to the bottom of the soil sample. The pedestal is connected with a metal cell (Figure 3.1 b), for the purpose of letting water flow out and flow in freely. The water level in the cell

should be maintained equal to the bottom of the soil sample to make sure of a smooth drainage.



a)



b)



c)

Figure 3.1 Experimental Device

The vertical displacement of the soil sample will be measured by a LVDT. The one we use is a model identified as SE-750-500, as shown in Figure 3.2. This kind of LVDT is specially designed for tests in subzero temperature ranges. The measure range of the LVDT is around 0.5" (12.7 mm) with a Full Scale Output (FSO) of ± 10 V, and the linearity error of the LVDT is $< 0.25\%$ of FSO. Besides, The LVDTs have an operational range of temperature that is between -20°C to 70°C . The core of the LVDT is fixed on the plunger using a rode attached to the top of the plunger.

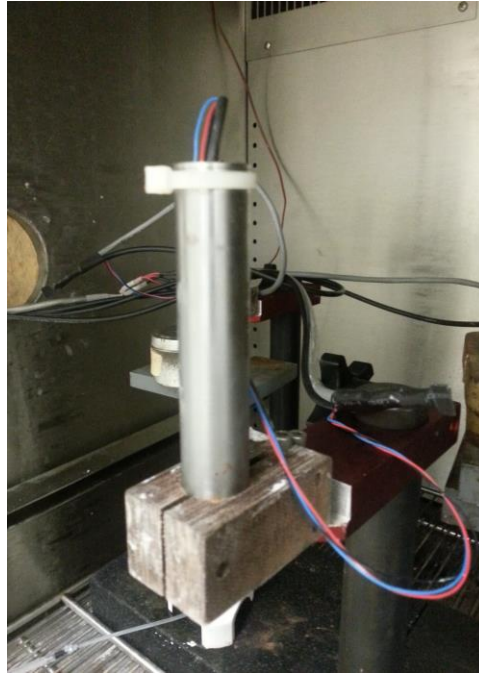


Figure 3.2 LVDT

The experimental setup is placed on a granite stand with an anodized aluminum mount for the LVDT. The whole experimental setup after assembling is shown in Figure 3.3 below.

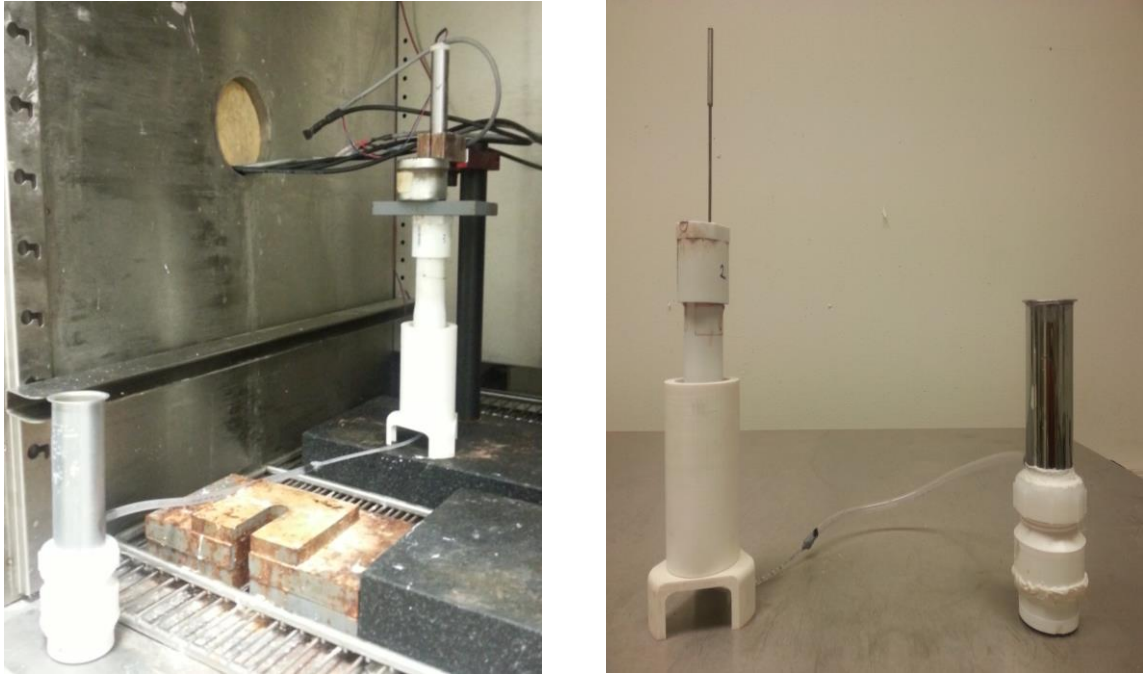


Figure 3.3 Whole Experiment Setup

Tests will be conducted under controlled conditions inside an environmental chamber as shown in Figure 3.4 below. The type of the chamber is a CSZ P500-8Z, which has a capacity of 64 cu. ft. with a temperature range from -50°C to 120°C . Also, the humidity inside the chamber can be modified from 0 to 1. The chamber is well insulated so to maintain the desired test conditions. Besides, temperature of the test samples inside the chamber can be measured by an in built thermocouple.



Figure 3.4 Experimental Chamber

The environmental chamber is convenient enough for it has been equipped with a touch screen controller, as shown in Figure 3.5 below. On the screen, we can change the temperature and humidity of the chamber, as well as control the temperature based on a desired thermocouple reading by just figure touching. Besides, we can design specific program files on our own to satisfy our tests requirement at any time, files can be started, stopped, modified and loaded into the chamber at any time during the tests.



Figure 3.5 Chamber Screen Controller

As for the soil sample adopted in this research, the first step was the physical characterization of the soil adopted in this research. A silt, SIL-75 from U.S. Silica Company was chosen in this thesis. This silt has a very low plasticity, and it is usually white in color, as shown in Figure 3.6 a). Routinely geotechnical tests were conducted to learn about the basic properties of this soil. Proctor and mechanical tests were also conducted to learn about the mechanical properties of this material. The Liquid Limit (LL) of it by cone test is 25.34%, and our target water content is around 30%, which is 1.2 times of the LL value. The LL value by cone test is shown in Figure 3.6 b) below.



Figure 3.6 Test Material

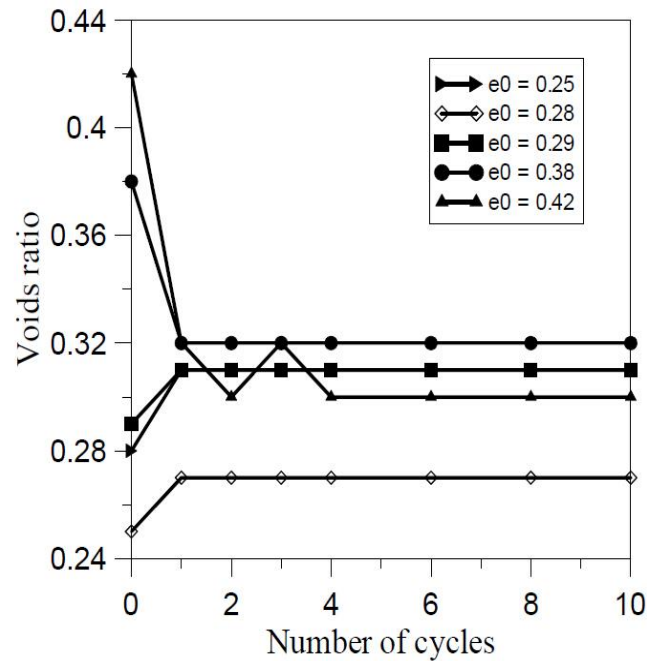
Slurry soil sample with a water content of 30% was chosen to perform tests for achieving the goal of fully saturated and evident test results. The mixture of soil with water will be prepared a day before the tests to make sure that there was no air voids formed. Then the soil sample will be placed into the mold. The surface of the sample should be taken care of to make sure that it is even before and after each loading and unloading step. More details will be elaborated in the next part.

Three devices with the same kind of soil material will be used at the same time for the purpose that tests can be compared with each other to make the results more accurate and effective.

3.3 Former cyclic freezing-thawing tests of frozen soils

In recent years, frozen soils subjected to cyclic freezing-thawing process have drawn more and more attention because of the increasing problems we meet in practical engineering design and construction. Study on mechanical behavior of frozen soils

subjected to cyclic freezing-thawing process is becoming another hot spot in research. Many cyclic freezing-thawing lab tests have been conducted by researchers. Volume changes in void ratios during freezing-thawing cycles were explored by Viklander in 1998. He conducted tests by using different initial void ratios, as shown in Figure 3.7. Lower initial void ratio showed expansion tendency, while high initial void ratio showed contraction tendency.



**Figure 3.7 Variation of Voids Ratios with Freezing-thawing Cycles
(Viklander, 1998)**

Other similar tests focusing on volumetric behavior of cyclic freezing-thawing in view of sample height were also conducted, like Konrad, (2010). Figure 3.8 shows the variation in height of sample with time and load.

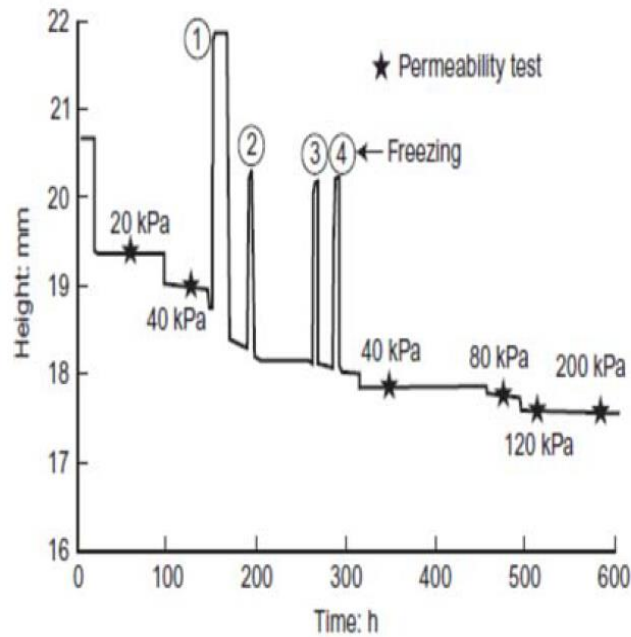


Figure 3.8 Variation of Soil Height with Loading and Time (Konrad, 2010)

Research about effects of cyclic freezing and thawing on mechanical properties of Qinghai–Tibet clay was done by Dayan Wang et al., (2007). Sample height, water content, stress–strain behavior, failure strength, elastic modulus, cohesion, and friction angle were measured in initial unfrozen soil as well as in subsequent thawed soil. They conclude that specimen height, water content, and cohesion decrease with the increasing of cycles, while friction angle increased with cycles. Failure strength and elastic modulus are influenced by cycles, while stress strain behavior is not. Figure 3.9 shows the change of failure strength with cycles under different loadings.

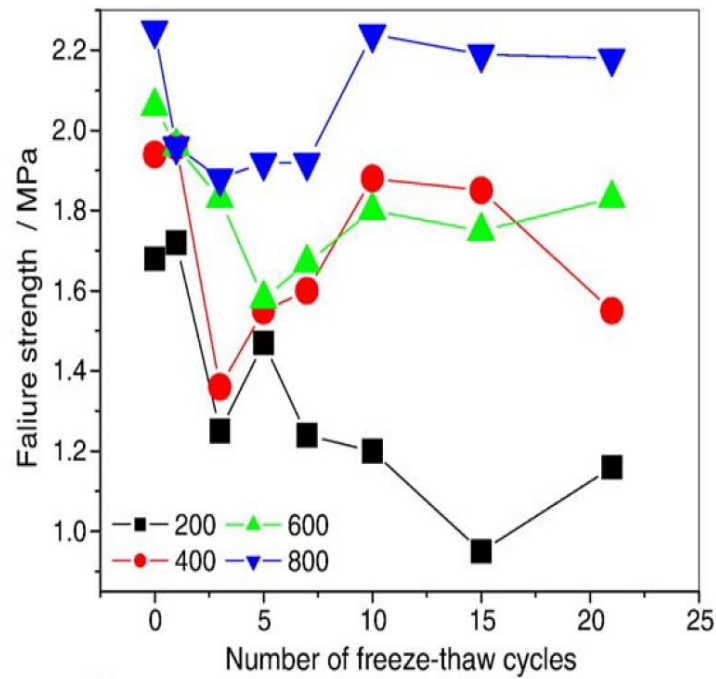


Figure 3.9 Failure Strength vs. Number of cycles (Dayan Wang et al., 2007)

The influence of freezing–thawing on engineering properties of a silty soil was studied by Jilin Qi et al., (2006). After cyclic freezing–thawing process until stable, changes in dry unit weight, strength parameters, pre-consolidation pressure, and modulus were examined to make clear the influence of cycles on them.

The main effects of cryogenic temperatures on mechanical behavior of frozen soils are similar to the influence of matric suction on unsaturated soils. All these tests demonstrate this, and these tests results also give a firm support for the idea to adapt modified BBM for the modeling of mechanical behavior of frozen soils subjected to cyclic freezing–thawing.

3.4 Cyclic freezing-thawing lab tests

In this part of the thesis, cyclic freezing-thawing tests with a temperature range from -7°C to 5°C are conducted in an environmental Chamber, in which temperature values between positive and negative can be set and circulated. Normally consolidated loose soil samples with pre-consolidation pressure of 10kpa and 100kpa are tested under same load steps together with over consolidated dense soil samples with pre-consolidation pressure of 500kpa and 1250kpa, so as to obtain ample tests results under different mechanical conditions, also, these results can be compared more effectively and obviously. Test data will be measured by LVDT, and values as well as plots will be recorded and shown by LabVIEW program on the computer connected.

3.4.1 Test procedure

These cyclic freezing-thawing tests will be performed according to fixed and carefully designed test procedure, which is elaborated in detail as follows:

1. Preparing the soil sample with water content of 30% a day before the tests, keeping it in the beaker sealed by plastic bag to make sure it is fully saturated and no moisture loss;
2. Mixing the sample carefully before the tests to make sure there is no air bubbles in the slurry sample;
3. Measuring the density and dry density after the sample is ready to use;
4. Setting up the device, making sure there is no air bubbles in the connection plastic tube (water will move smoothly), putting soil sample into the mold with the surface even;

5. Loading to increase pre-consolidation pressure by load frame is necessary (e.g. pre-consolidation 500kpa and 1250kpa);
6. Putting filter paper and metal cylinder on the top of the sample;
7. Moving device into chamber, starting the LabVIEW LVDT program file on the computer, putting plunger which is connected to the LVDT on top of the device;
8. Placing loads to target value; after consolidation process, starting the cyclic freezing-thawing chamber file by the screen controller;
9. Performing three tests together at one time, recording the displacement and void ratio changes every cycle, drawing the void ratio vs. cycle number curve for this cyclic process until the change is stable for at least 3 cycles for all three tests, starting next load step as above.
10. Similar cyclic tests with same procedure will be performed with different initial pressure conditions and loading-unloading conditions.

3.4.2 Test results

For the purpose of collecting enough test data for mechanical modeling, loose soil sample tests and dense soil sample tests are performed separately. All the tests samples will share the same initial properties and conditions, as is shown in Table 3.1 below.

Table 3.1 Soil Property Parameters

Height(m)	0.039
Diameter(m)	0.039
V(m3)	4.6589E-05
A(m2)	0.001194591
Gs	2.65
w(%)	30.19
Density(kg/m3)	1757.71
Dry Density(kg/m3)	1350.11
Sr	1
Metal h(m)	0.013
Top Ring h(m)	0.005162
Metal+Plunger	0.22165
e0	0.8

3.4.2.1 Loose soil sample

As for loose soil sample, test with a pre-consolidation pressure of 10kpa before cycling is done firstly, and the consolidation curve showing volume changes after cyclic freezing-thawing under three different loading steps (denoted 1, 2, and 3) is shown in Figure 3.12 below.



Figure 3.10 Loose Soil Sample with pre-10kpa

Void ratio changes with cyclic freezing-thawing processes under different pressure conditions are recorded by LVDT, and the results (on the right side) as well as their corresponding parts in consolidation curve (on the left side) are shown in Figure 3.13 below. The load steps are 10kpa-Cycling-100kpa-Cycling-10kpa-Cycling. C will be used as Cycling for short in the following illustration.

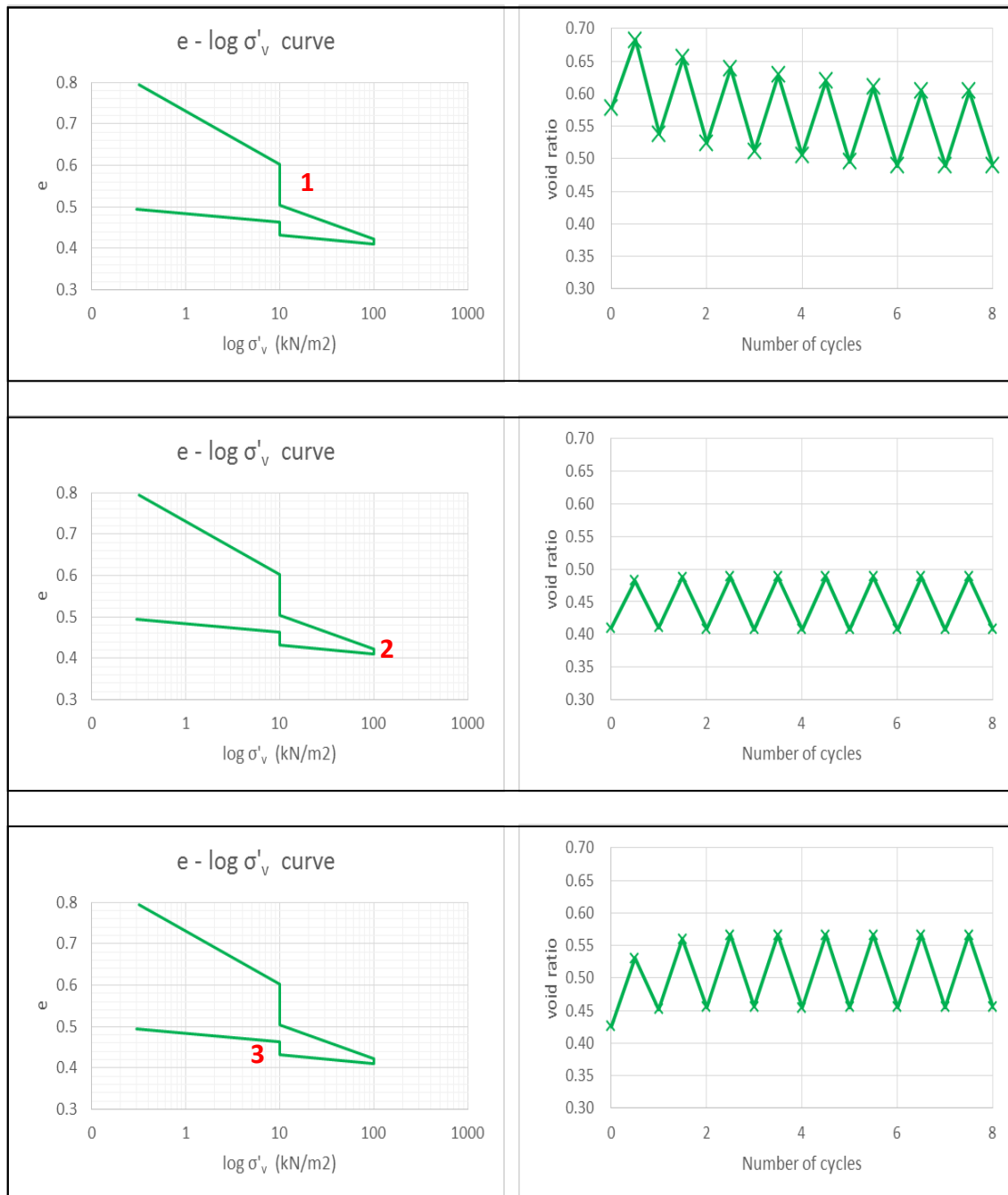


Figure 3.11 Void Ratio versus Freezing-thawing Cycles of Sample One

It can be observed from the figure that volume change will finally get stable after several cycles when a residual value is reached. When soil sample cycles at 10kpa and 100kpa as normally consolidated soil, it shows a behavior of compaction. After unloading to 10kpa, it becomes over consolidated soil, and it shows a behavior of expansion.

As for loose soil sample with a pre-consolidation pressure of 100kpa before cycling is also conducted, and the consolidation curve showing volume changes after cyclic freezing-thawing under three different loading steps (denoted 1, 2, and 3) is shown in Figure 3.14 below. The load steps are 100kpa-C-10kpa-C-100kpa-C.

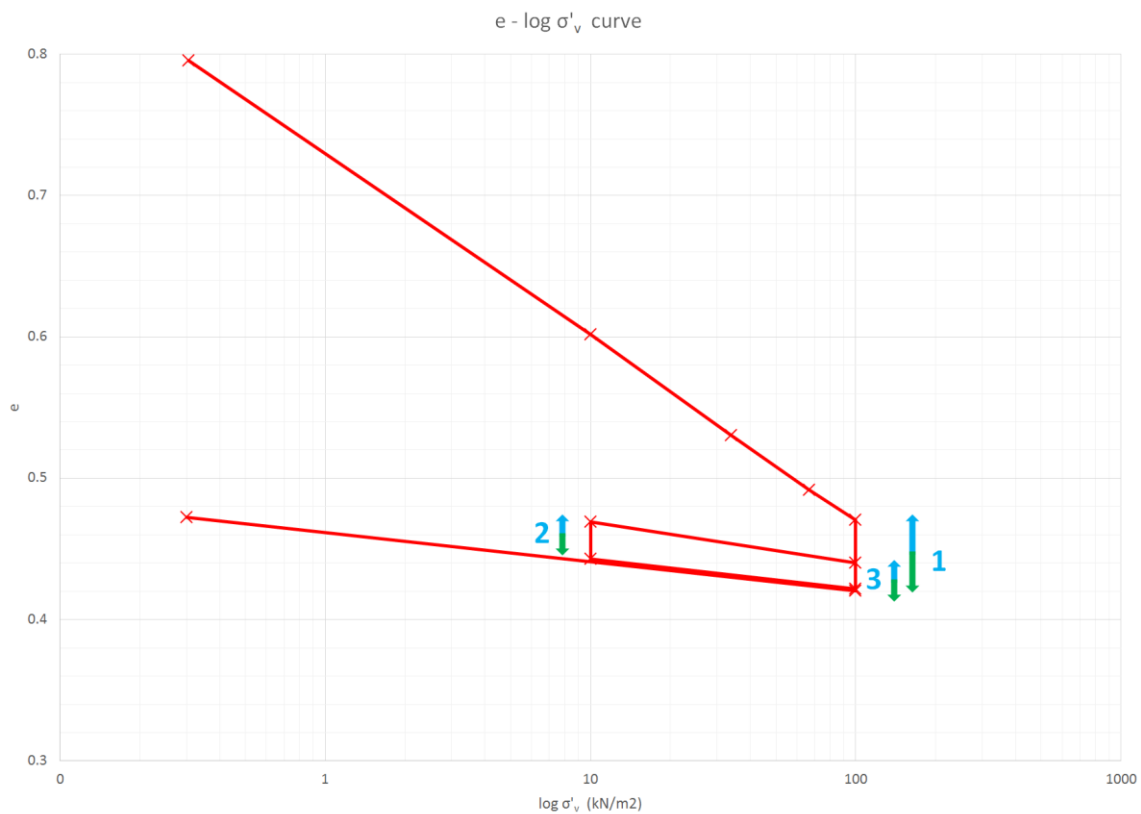


Figure 3.12 Loose Soil Sample with Pre-100kpa

Void ratio changes with cyclic freezing-thawing processes under different pressure conditions are shown in Figure 3.15 below.

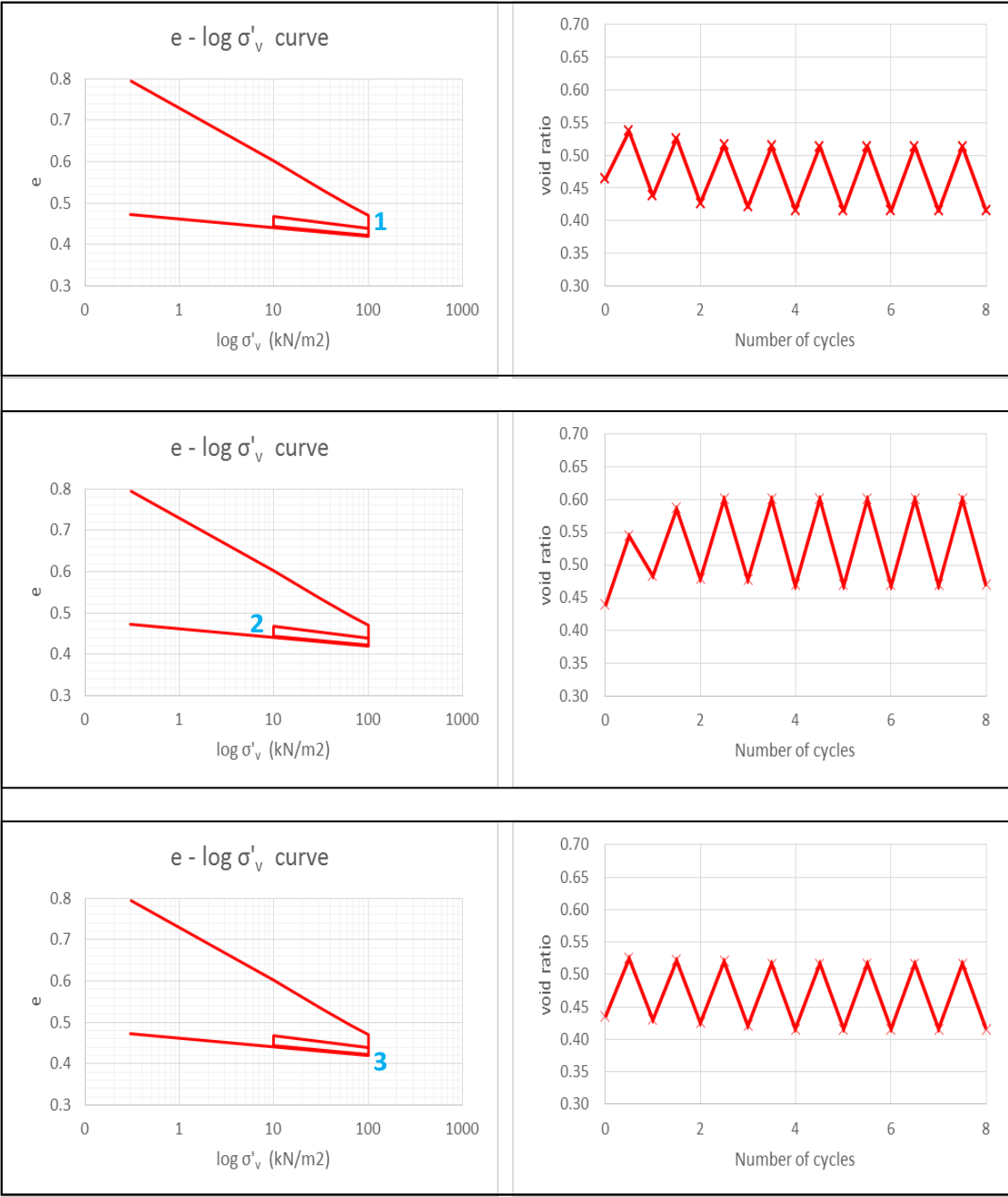


Figure 3.13 Void Ratio versus Freezing-thawing Cycles of Sample Two

Similar behaviors are observed on this condition. When soil sample is loaded to 100kpa and reloaded to 100kpa, it shows tendency of contraction because soil is normally consolidated, and soil particles are rearranged due to freezing-thawing cycles.

3.4.2.2 Dense soil sample

As for dense soil sample, two different pre-consolidation pressures are imposed. One is 500kpa and the other one is 1250kpa. The consolidation curve showing volume changes after cyclic freezing-thawing under three different loading steps (denoted 1, 2, and 3) is shown in Figure 3.16 below. The load steps of it are in an order of 500kpa-10kpa-C-100kpa-C-10kpa-C.

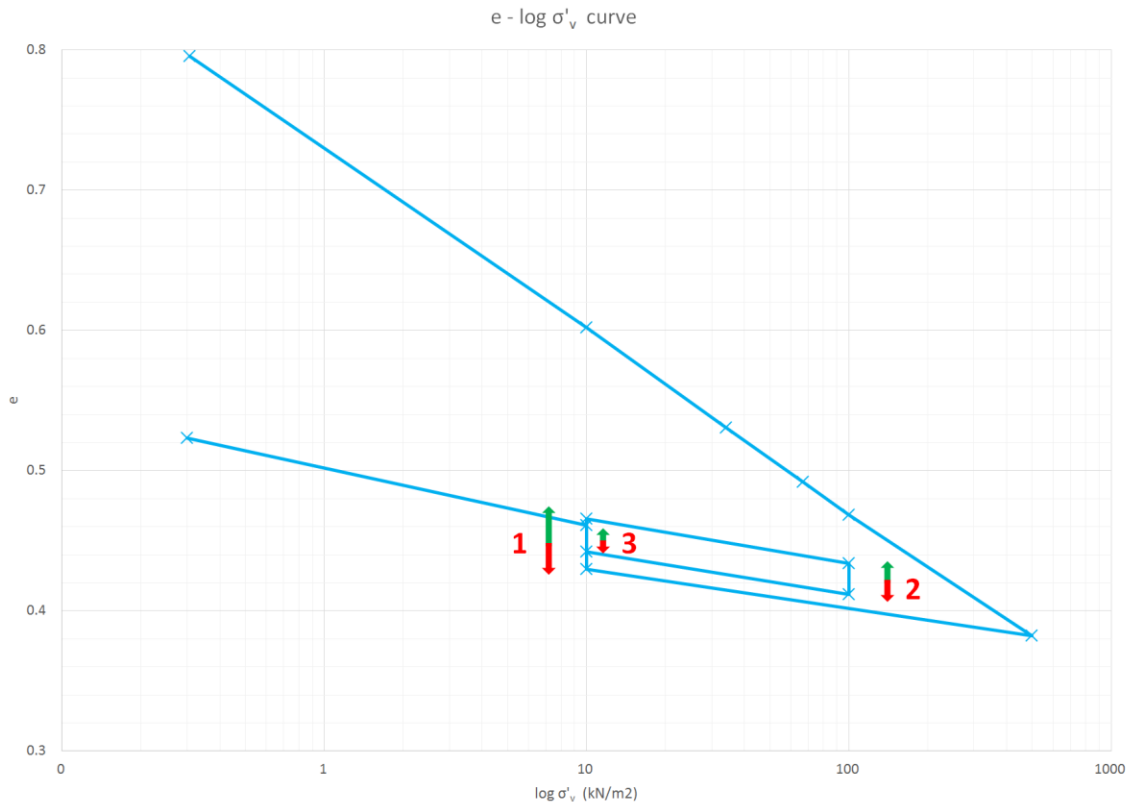


Figure 3.14 Dense Soil Sample with pre-500kpa Condition One

Void ratio changes with cyclic freezing-thawing processes under different pressure conditions are shown in Figure 3.17 below.

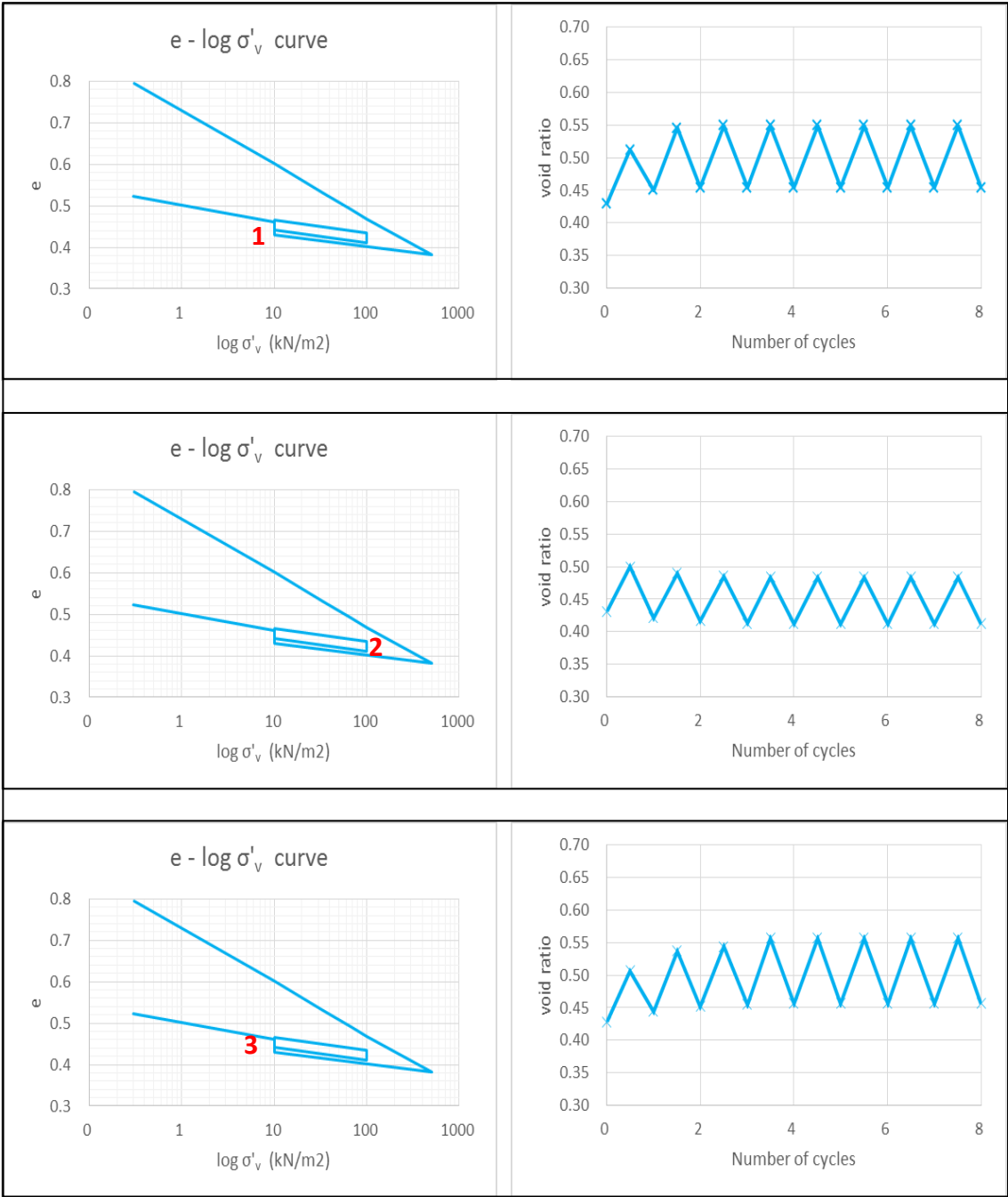


Figure 3.15 Void Ratio versus Freezing-thawing Cycles of Sample Three

As for dense soil sample with a pre-consolidation pressure of 500kpa but different load steps of 500kpa-100kpa-C-10kpa-C-100kpa-C, the consolidation curve showing volume changes after cyclic freezing-thawing under three different loading steps (denoted 1, 2, and 3) is shown in Figure 3.18 below.

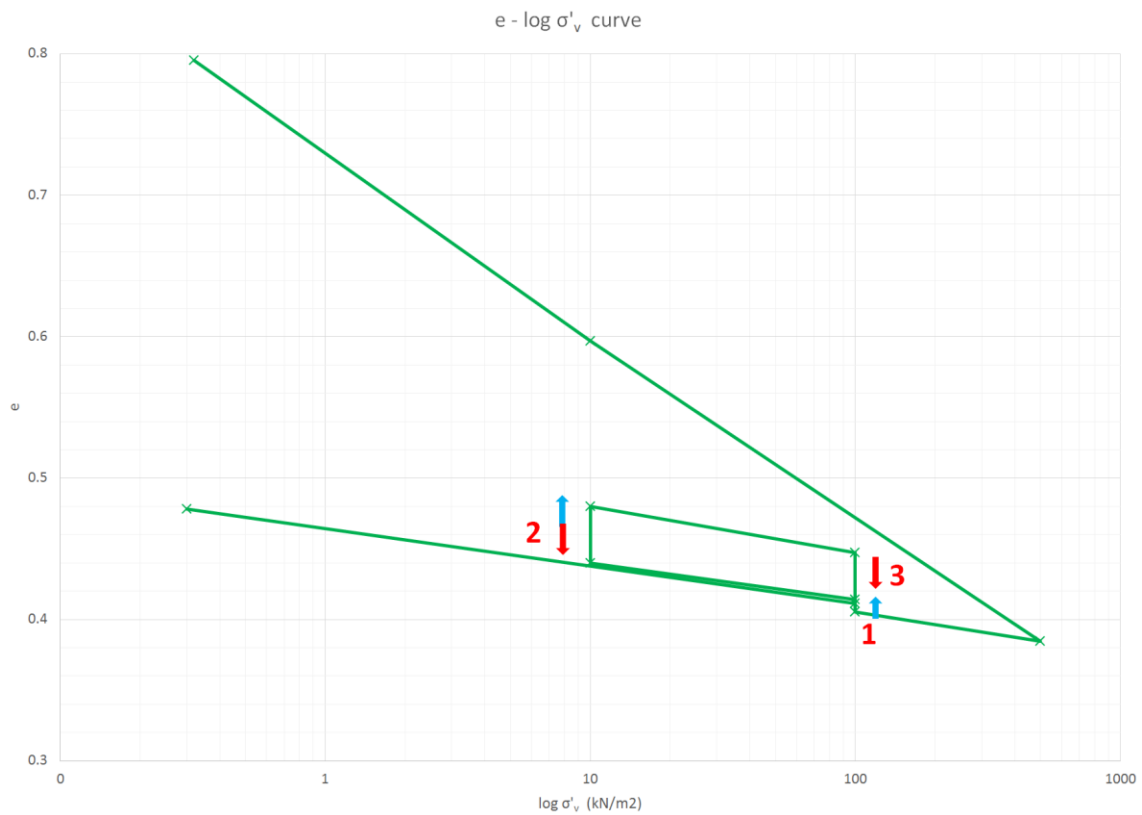


Figure 3.16 Dense Soil Sample with pre-500kpa Condition Two

Void ratio changes with cyclic freezing-thawing processes under different pressure conditions are shown in Figure 3.19 below.

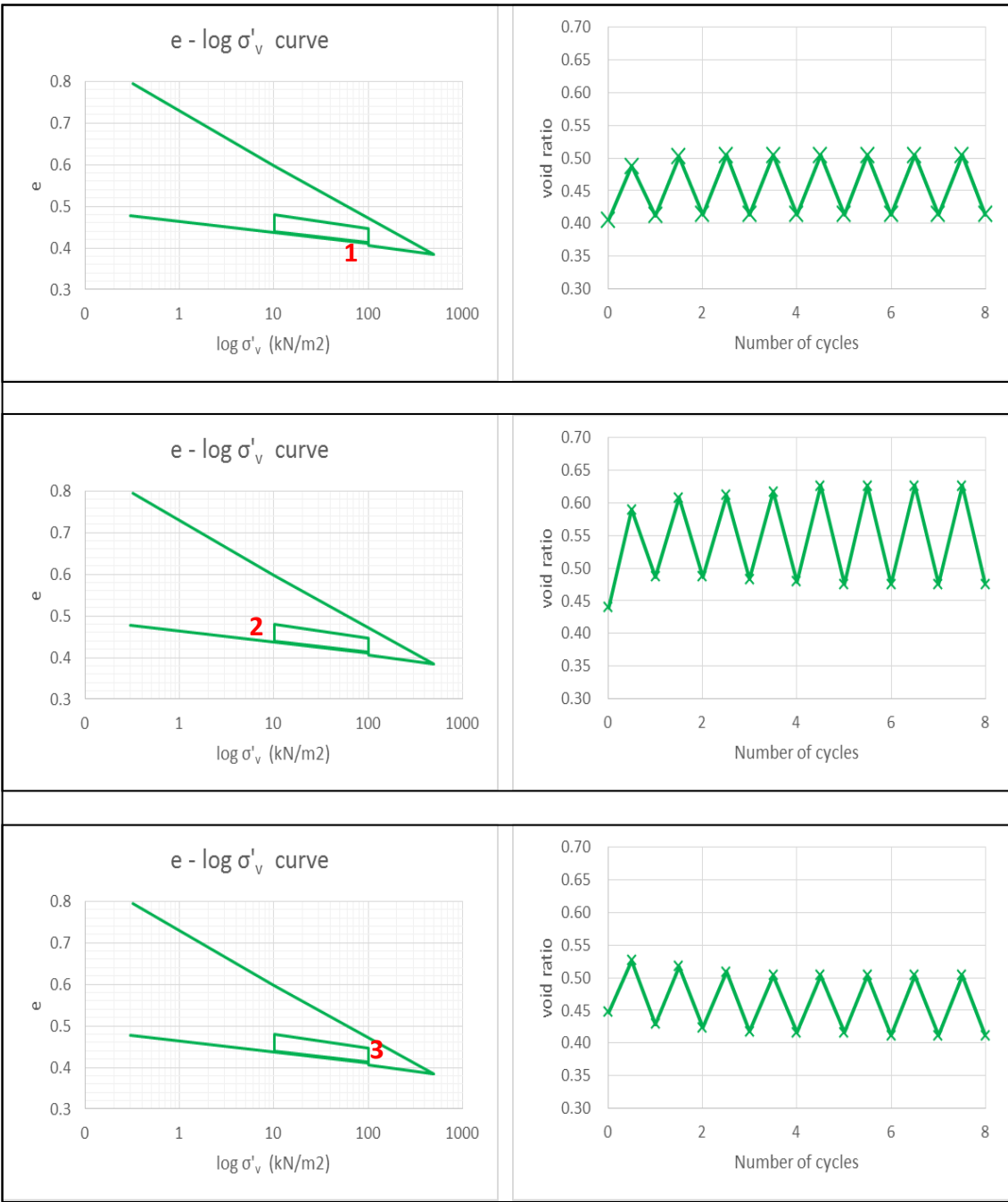


Figure 3.17 Void Ratio versus Freezing-thawing Cycles of Sample Four

It is easy to find that this test shows a different behavior when first load to 100kpa after consolidation with a pre-consolidation of 500kpa, it does not contract but expand, this is because volume increases during freezing but cannot get back to initial status during thawing cycles. It is the result of the change in openness of soil structure when under a different loading condition.

The other higher over-consolidated samples will be subjected to a pre-consolidation pressure of 1250kpa. Consolidation curve showing volume changes after cyclic freezing-thawing under three different loading steps (denoted 1, 2, and 3) is shown in Figure 3.20 below. Load steps of it are 1250kpa-10kpa-C-100kpa-C-10kpa-C.

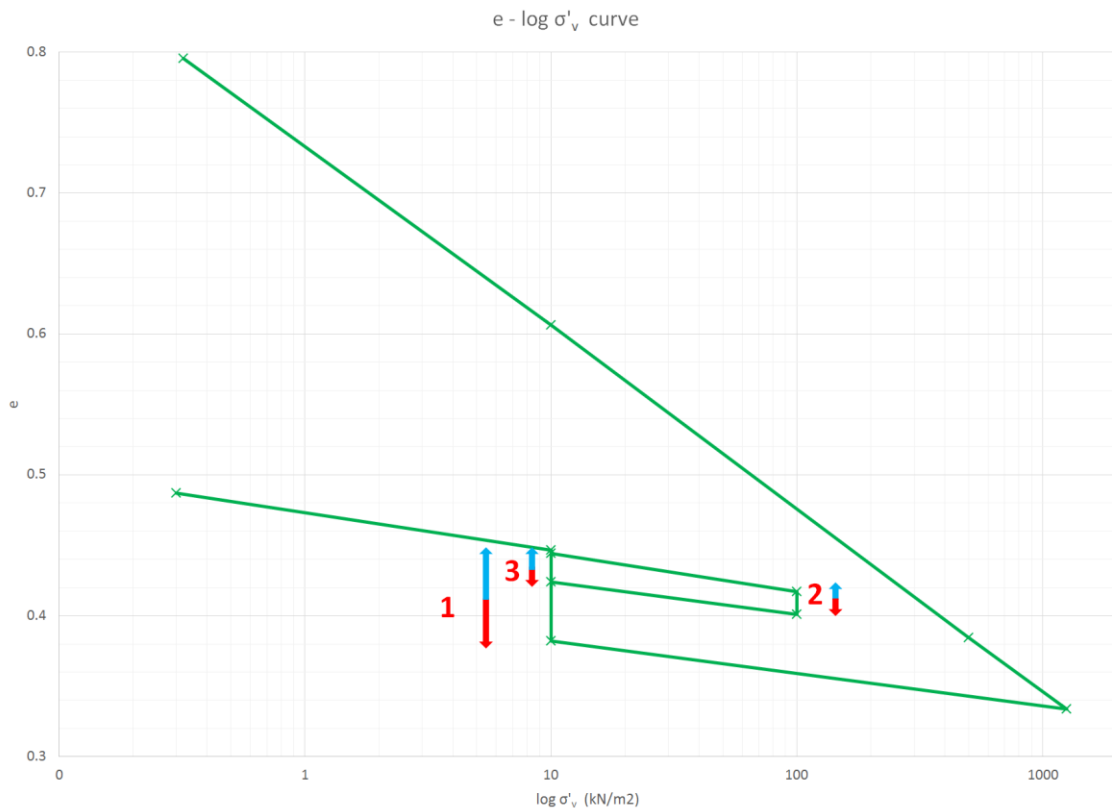


Figure 3.18 Dense Soil Sample with pre-1250kpa Condition One

Void ratio changes with cyclic freezing-thawing processes under different pressure conditions are shown in Figure 3.21 below.

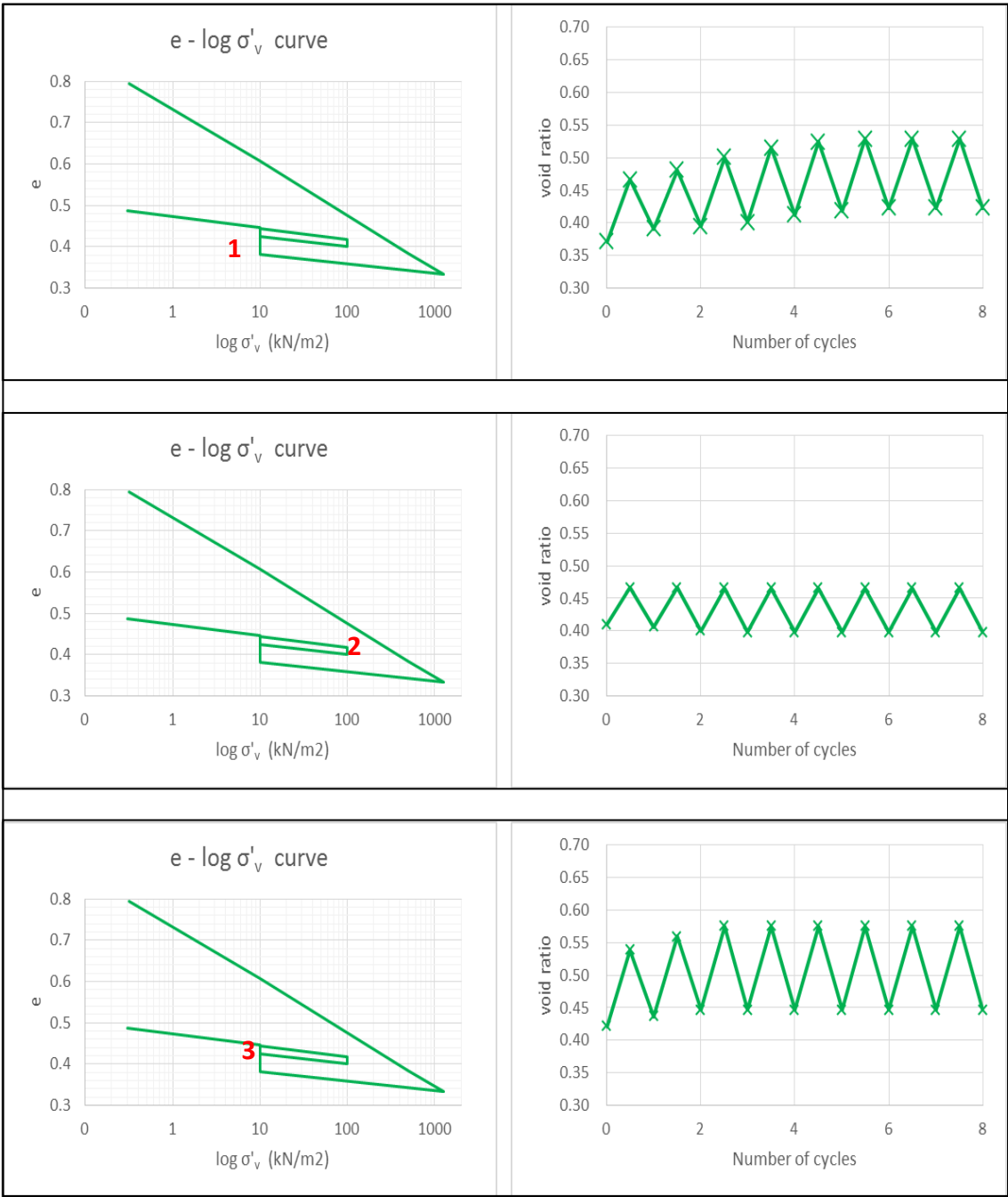


Figure 3.19 Void Ratio versus Freezing-thawing Cycles of Sample Five

As for dense soil sample with a pre-consolidation pressure of 1250kpa but different load steps of 1250kpa-100kpa-C-10kpa-C-100kpa-C, and the consolidation curve showing volume changes after cyclic freezing-thawing under three different loading steps (denoted 1, 2, and 3) is shown in Figure 3.22 below.

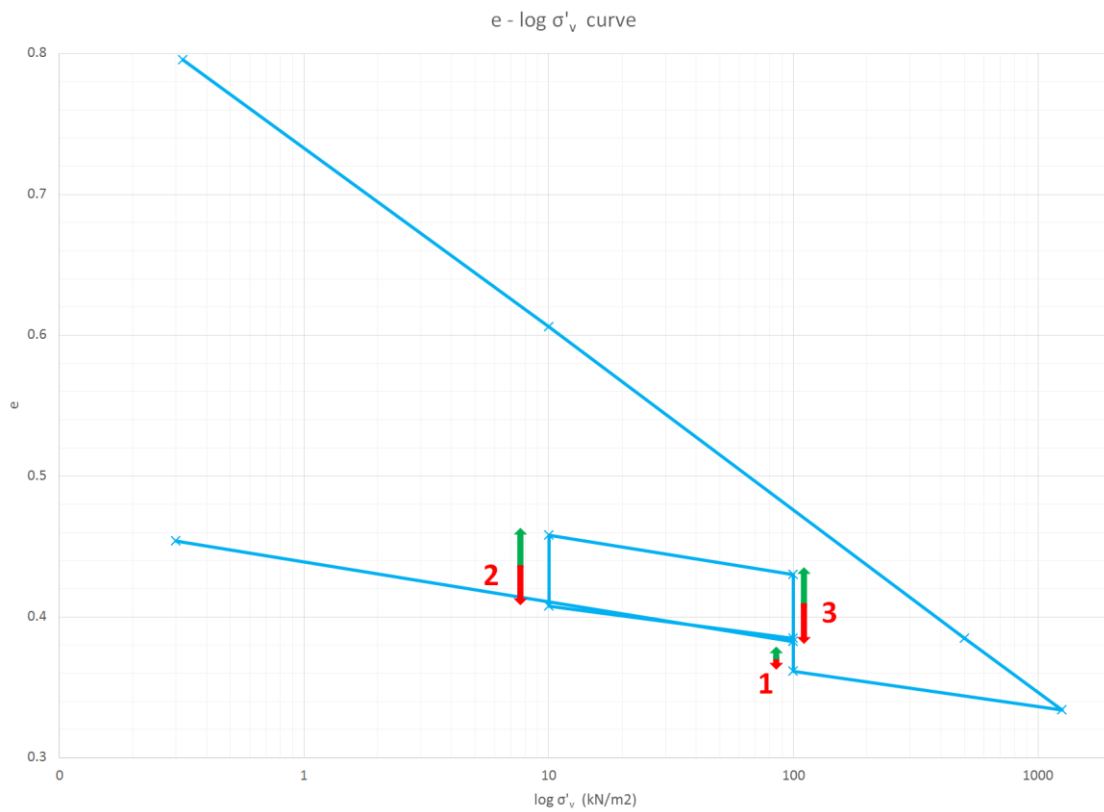


Figure 3.20 Dense Soil Sample with pre-1250kpa Condition Two

Void ratio changes with cyclic freezing-thawing processes under different pressure conditions are shown in Figure 3.23 below.

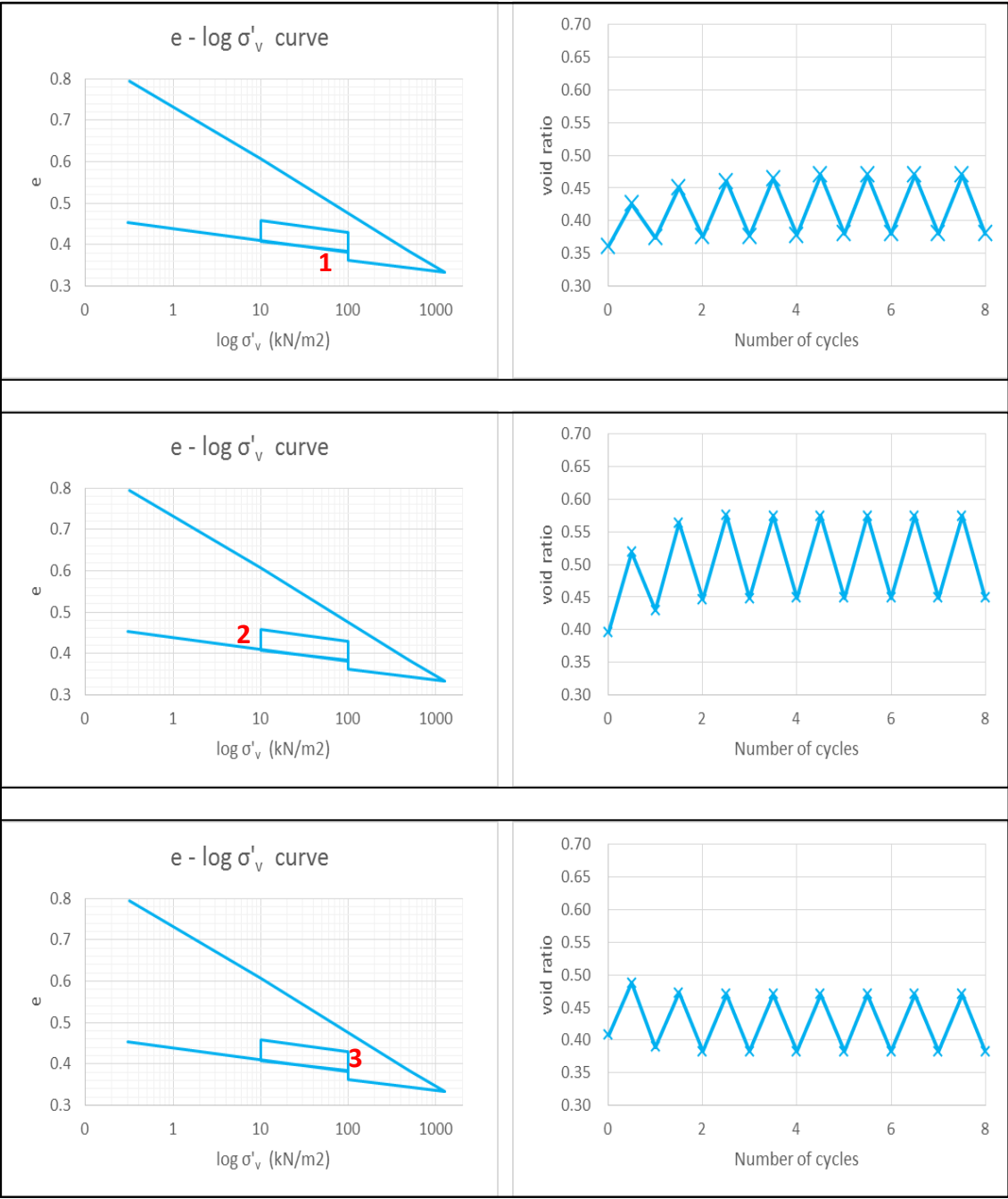


Figure 3.21 Void Ratio versus Freezing-thawing Cycles of Sample Six

It is observed that tests with higher pre-consolidation pressure show similar mechanical behavior as those with lower pre-consolidation pressure. However, volume expansion is higher for soil with a pre-consolidation of 1250kpa than soil with a pre-consolidation pressure of 500kpa. It is because of soil structure differences, and the next section will explain this comprehensively.

3.4.3 Test comparison and summarization

For the purpose of better understanding volume change during the cyclic freezing-thawing tests, Comparisons between similar load steps will be an effective way to achieve this goal. Figure 3.24 shows the comparisons under same load steps (pre-consolidation pressure-10kpa-C-100kpa-C-10kpa-C). Columns from a) to c) demonstrate volume changes during freezing-thawing process according to a pre-consolidation pressure of 10kpa, 500kpa, and 1250kpa.

We can notice that after several freezing-thawing cycles, volume change will become stable for all tests. When firstly put 10kpa loading (shown in first horizontal row), for loose soil in a), volume shows a collapse behavior, while for dense soil samples in b) and c), volume shows a expansion behavior. Besides, soil sample with pre-consolidation of 1250kpa expands more than soil sample with pre-consolidation of 500kpa. The residual values after freezing-thawing cycles on same load condition are close to each other.

Similarly, Figure 3.25 shows the parallel results under same load steps (pre-consolidation pressure-10kpa-C-100kpa-C-10kpa-C). Columns from a) to c) demonstrate volume changes during freezing-thawing process according to a pre-consolidation

pressure of 10kpa, 500kpa, and 1250kpa. Conclusions to draw are similar as those from Figure 3.24. An explanation in micro scope on these mechanical behaviors will be forwarded in next section.

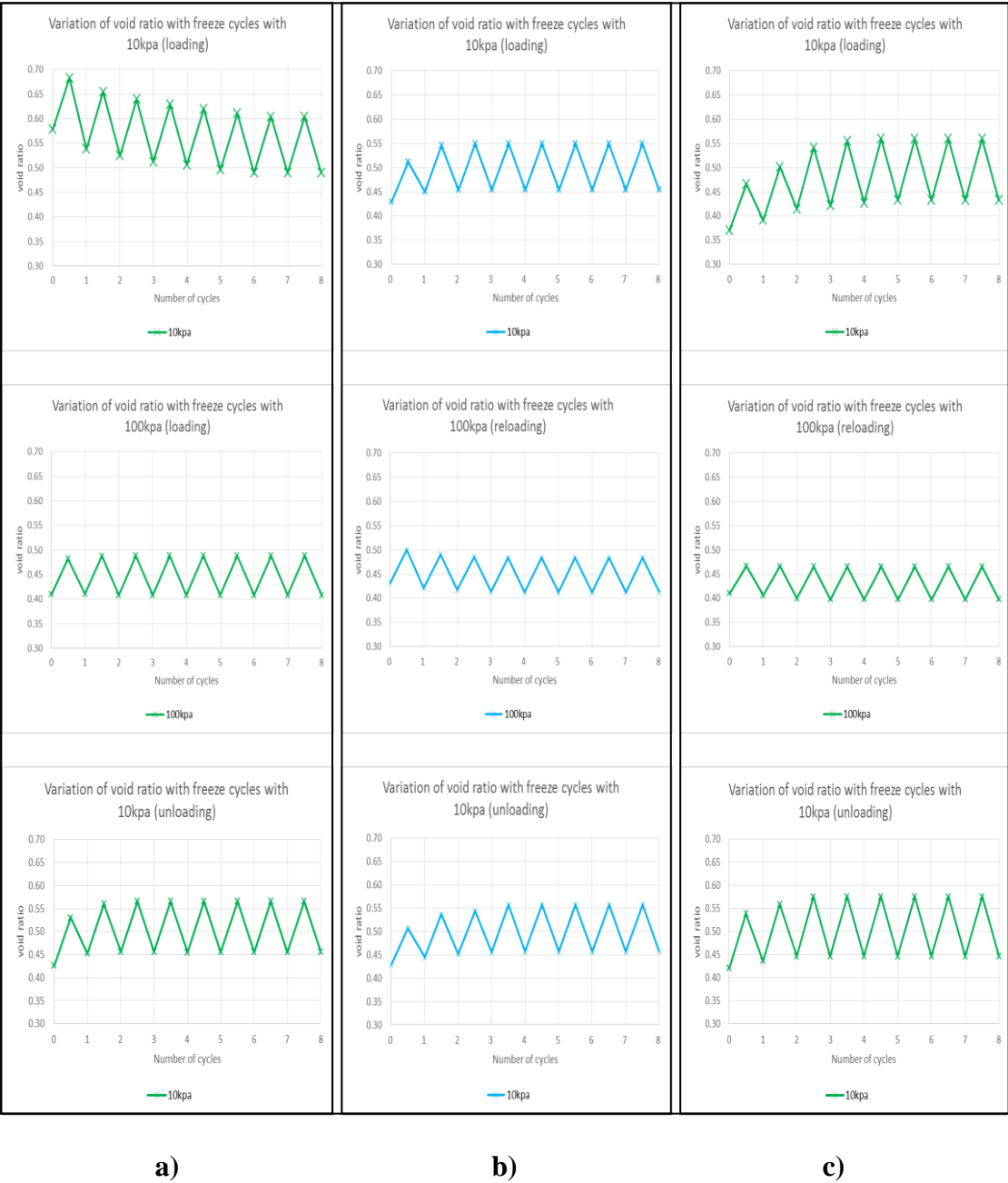
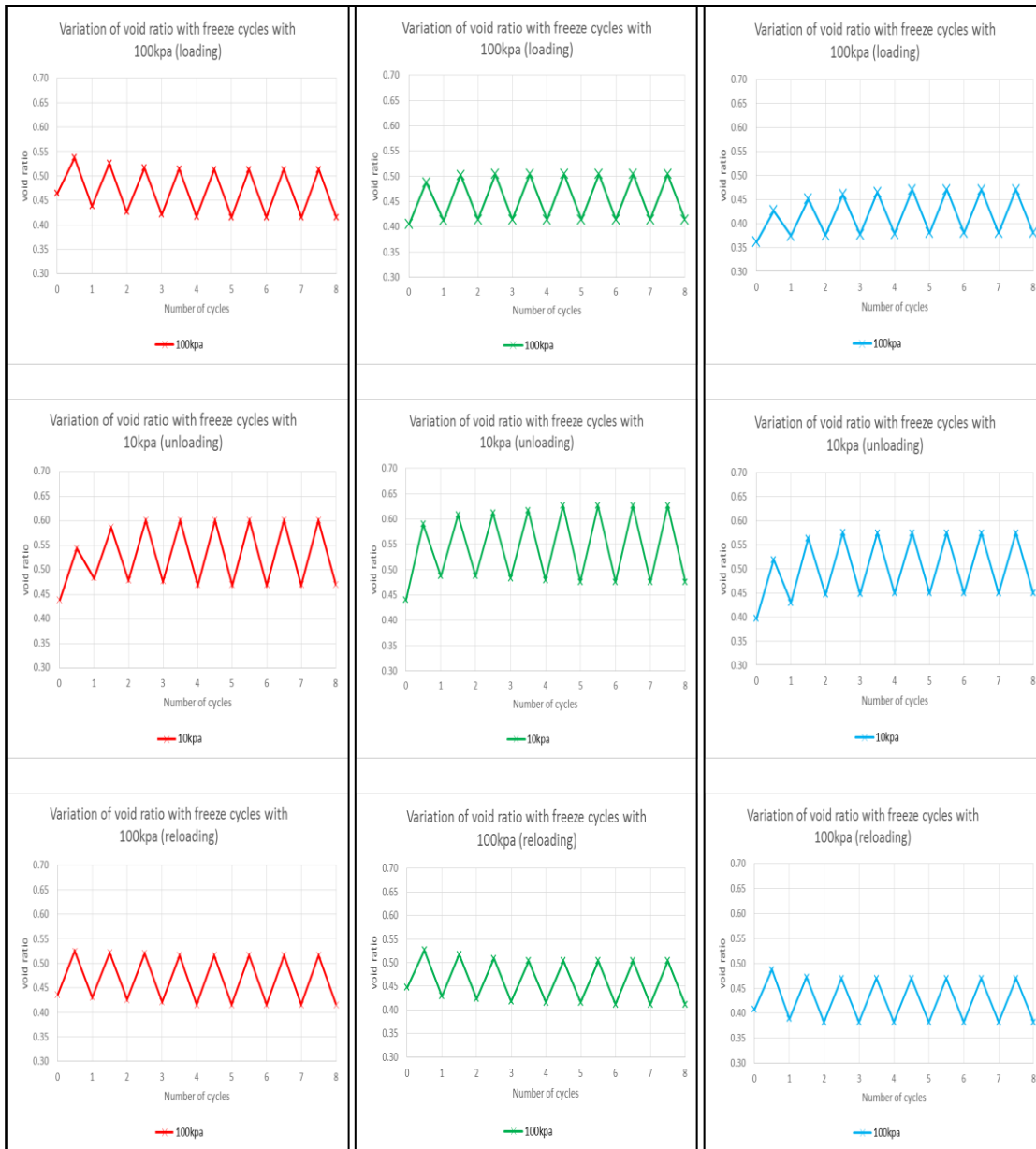


Figure 3.22 Comparison under 10kpa-100kpa-10kpa load step



a)

b)

c)

Figure 3.23 Comparison under 100kpa-10kpa-100kpa load step

To wrap up, from the test results, we can draw conclusions as follows:

- Soil samples with different history in term of loading (i.e. NC and OC) and F-T cycles behave differently in terms of volume change;
- Loose soil samples show a tendency to contract while dense soil samples show a tendency to expand;
- The range of volume change during freezing-thawing cycles under higher loads is smaller than that under lower loads;
- After a series of freezing-thawing cycles, the volume changes tend to become stable.

4 MECHANICAL MODEL FOR CYCLIC FREEZING-THAWING SOIL

4.1 Introduction

The modeling activities have been focused on developing a constitutive model for soils subjected to freezing-thawing cycles and its validation against the experimental data generated in this project and also already published one. In this section of the thesis, how to achieve this goal will be demonstrated in detail. It will contain an introduction of models incorporated in this mechanical model, how the model behaves, and cases comparisons in dense soil and loose soil between modeling results and experimental results.

4.2 Models incorporated in this research

The mechanical model developed in this research is closely connected to two models; one is the Barcelona Basic Model (BBM), and another one is the double structure generalized plasticity model. This research will mainly combine these two to model the volumetric behavior of cyclic freezing-thawing frozen soil. These will be elaborated in detail in the following part.

4.2.1 Barcelona Basic Model (BBM)

The Barcelona Basic Model (BBM) is firstly stated by Gen, Alonso and Josa in 1990. It is a model developed from the Cam Clay Model, and it takes suction into consideration. The Cam Clay Model is for the condition where suction is equal to zero, which means soil is fully saturated, while BBM is for the condition where suction is not zero, which means soil is partly saturated. The two main stress variables for BBM are net stress and suction.

Volume changes mainly depend on stress level, which is defined as p-loading. Suction will increase pre-consolidation pressure, so the yielding point will be different when suction is different. The indexes of consolidation are different also, which is shown in Figure 4.1 below.

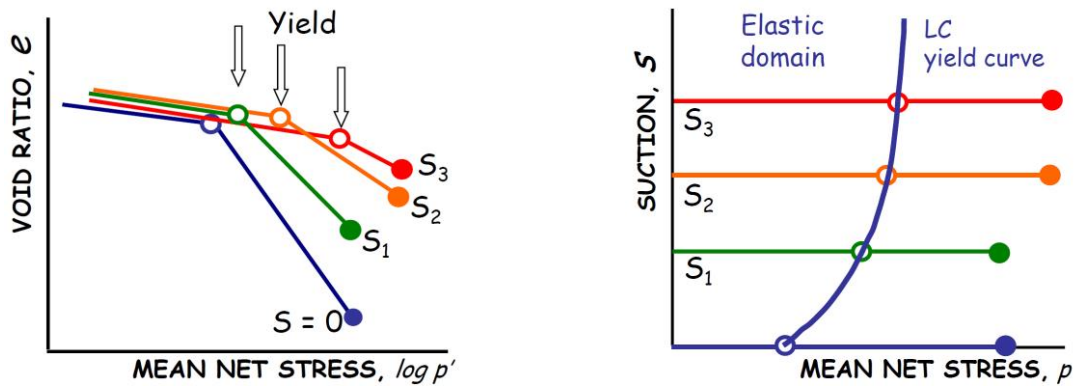


Figure 4.1 Effect of Suction

Suction can also lead to irreversible volume change during wetting and drying, which is defined as s-loading. The existence of suction increases the elastic domain and shear strength of soil, which can be shown by BBM in an isotropic plane and a deviatoric plane, as Figure 4.2 below.

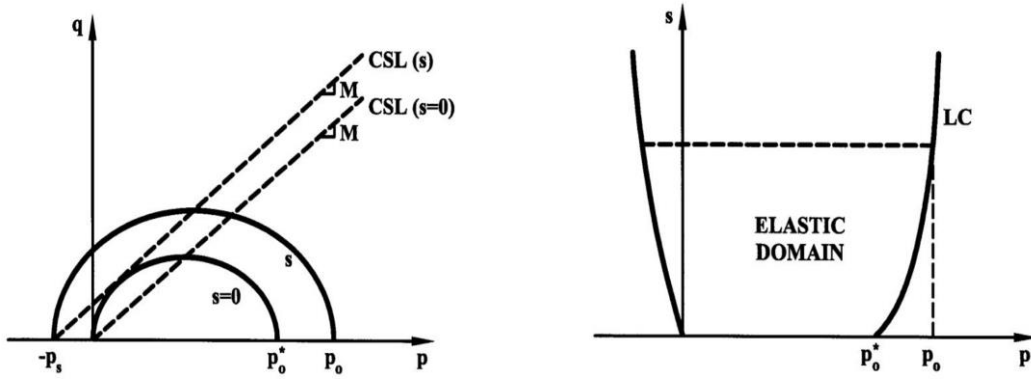


Figure 4.2 Barcelona Basic Model

The formulas for this model, such as yield surface, hardening laws will be listed in Appendix A.

BBM is extended from unsaturated soil to frozen soil firstly by Nishimura et al. in 2009. When soil is fully saturated before freezing, air can be totally replaced by ice when frozen. Matric suction in BBM can be replaced by cryogenic suction as described in Section 2.

Cryogenic suction can cause volume change, and it will also increase the elastic domain and shear strength as matric suction does. As for the frozen soil study, BBM is modified with new defined net stress σ_n and cryogenic S_c in Eq. 4.1.

$$\sigma_n = \sigma - \max(P_i, P_l, 0) \quad (4.1)$$

$$S_c = \max(P_i - P_l, 0)$$

Where σ is the mean stress, σ_n is the net stress.

Cryogenic suction changes with temperature changes (e.g. freezing and thawing). The yield function, hardening law, and flow rule in BBM can also be modified to be applied in frozen soil, and this point was demonstrated by Nishimura as well as some other researchers.

4.2.2 Double structure plasticity model

The double structure generalized plasticity model for expansive materials is created by Marcelo Sanchez et al., (2005), and it was developed from the expansive clay model, firstly created by Alonso et al., (1999). In double structure model, soil is divided into two structures: microstructure and macrostructure. The macrostructure is composed by the global arrangement of clay aggregates with macro pores between them, while the microstructure is the active clay minerals and their vicinity. Figure 4.3 below shows the two structures in their expansive clay models.

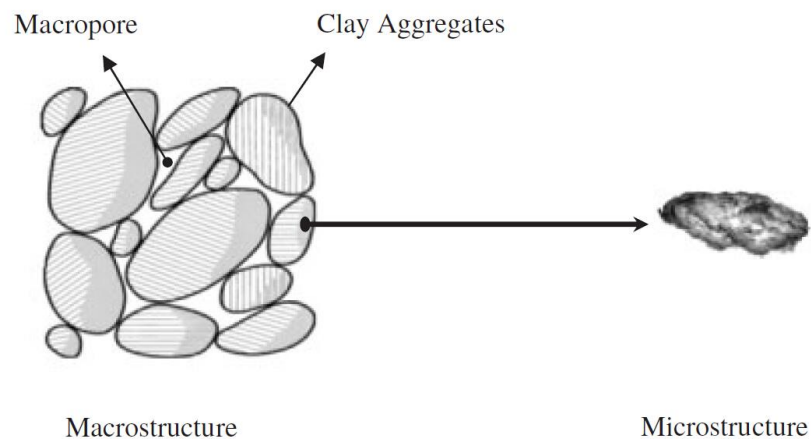


Figure 4.3 Double Soil Structures (Sanchez et al., 2005)

In double structure model, they gave introduction to the macrostructure model, microstructure model, and also the interaction model between these two structures.

The macrostructure model is using the Barcelona Basic Model (BBM), for it is an elasto-plastic strain hardening model, and is able to model the behavior in many non-expansive soils. The macrostructure for our model is macro-pores and silt aggregates.

The microstructure model they proposed is an elastic model, for physic-chemical phenomenon at this level is considered as reversible, and the microstructure phenomenon is elastic and volumetric. The effective stress is the sum of mean stress and suction with factor. For expansive soil, it is the elastic expansion and contraction of the soil partials due to the wetting and drying process, while in our model for frozen soil, phase change between ice and water during the freezing and thawing process is considered as this elastic part. The phase change is also elastic and reversible.

The interaction model is to illustrate how the macrostructure and microstructure interact with each other, and as a result of which the behavior of expansive materials can be described more systematically and comprehensively. They applied this model to a cyclic wetting and drying test, which is very comparable to our cyclic freezing and thawing test. They put 0.1Mpa and 0.01Mpa loads for two tests with the same suction from 0.2Mpa to 1.7Mpa. The tests results and model results are as follows in Figure 4.4.

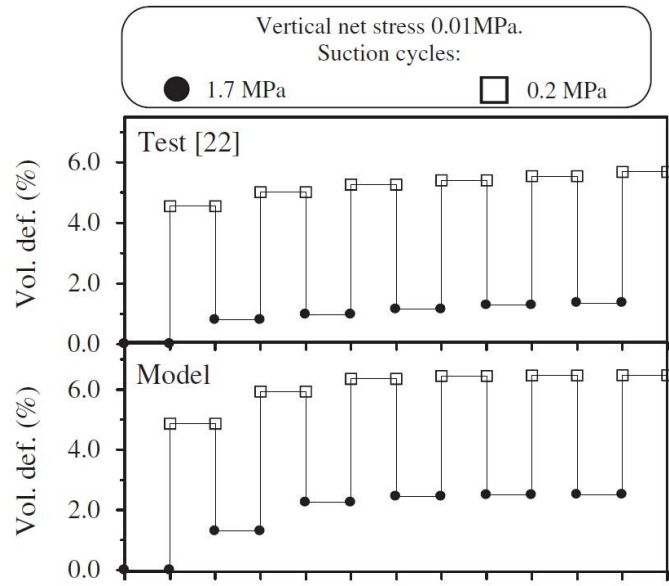


Figure 4.4 Volumetric Deformations in Test and Model (Sanchez et al., 2005)

The interaction curve is shown in Figure 4.5. Both of the two tests are developed on the left side of point E, which is the equilibrium point.

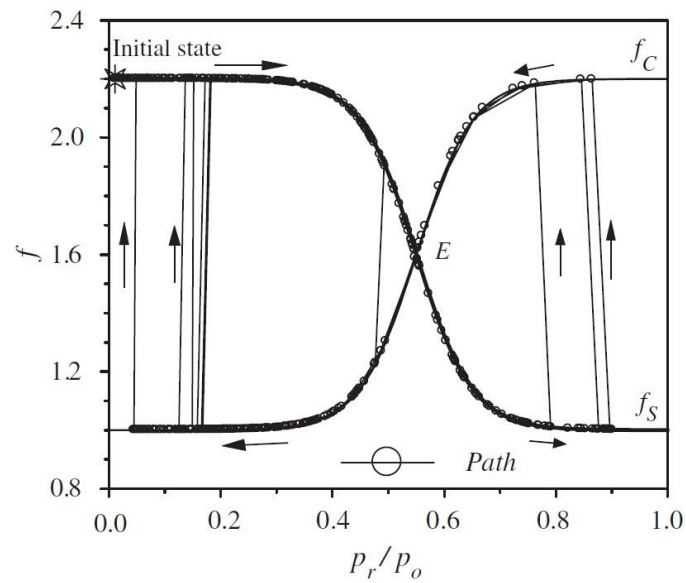


Figure 4.5 Interaction Curve (Sanchez et al., 2005)

In this thesis, we will apply the interaction model that simulates the cyclic wetting-drying process of expansive material to the cyclic freezing-thawing process of frozen soil. Macrostructures and microstructures in these two kinds of soils are similar, and cyclic suctions exist in both of them. Our tests are all under same loading, 0.1Mpa or 0.01Mpa, so as to be compared to expansive soil at the same time and studied in a similar way. The interaction model for frozen cyclic freezing-thawing soil will be elaborated in next part.

4.3 Interaction model for cyclic freezing-thawing soil

As introduce above, in expansive clay model, the elastic deformation of the soil within the yield surface is due to clay mineral expansion. Similarly, phase change from water to ice can also be just like the mineral expansion. Inspired by this similarity, a mechanical model for frozen soils subjected to the cyclic freezing-thawing process will be presented here.

The deformation occurred in the soil can be divided into two parts, one is elastic, and the other one is plastic. The strain we talk about is the sum of them, which is shown in Eq. 4.2 below.

$$\dot{\epsilon} = \dot{\epsilon}^e + \dot{\epsilon}^p \quad (4.2)$$

The elastic deformation can be decomposed into four parts: ice formation, suction, mechanical actions and thermal actions. The relationship is shown in Eq. 4.3 below.

$$\dot{\epsilon}^e = \dot{\epsilon}^i + \dot{\epsilon}^s + \dot{\epsilon}^m + \dot{\epsilon}^t \quad (4.3)$$

As we all know, phase change from water to ice will cause volume change. We consider this ice formation as elastic strain, and the volume change during freezing or thawing by phase change is about 9% of the water volume involved in this process. Therefore, this depends on the change in the degree of ice. The elastic strain due to ice formation can be described in Eq. 4.4 below.

$$\dot{\epsilon}^i = \dot{S}_i \times \alpha \times n \quad (4.4)$$

n is porosity, and α is the expansion of ice due to phase change, which is 9%.

Though volume changes due to suction and temperature will also happen, they are negligible compared to the other factors. If necessary, they can be incorporated in the future, but for this model, we will mainly take ice formation and mechanical factors into consideration.

The volume changes during the freezing and thawing processes are different for loose soil and dense soil. Loose soils have an open structure, which will cause rearrangement when freezing and thawing. For loose soil, freezing is always connected to expansion, while thawing is always connected to contraction. This is because in thawing for loose soils, the unstable rearrangement has a collapse when ice returns to water. The current state is denser than before, and lesser collapse will happen in the following cycles until it becomes stable. For dense soil, it will expand in freezing, but in thawing it cannot return to its initial status, and it looks like the soil expands after cycles until it finally becomes stable. The schematic of differences in volume change for these two kinds of soils are shown in Figure 4.6 below.

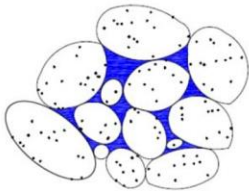
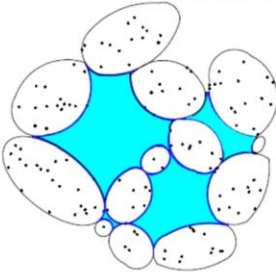
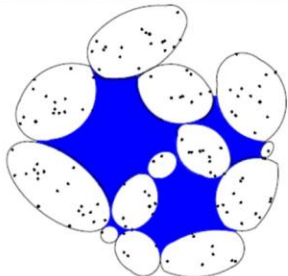
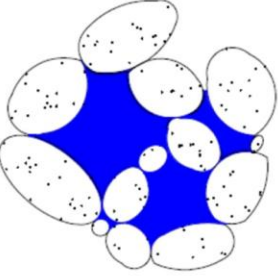
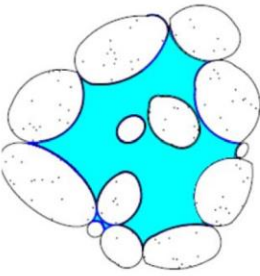
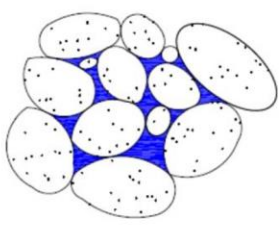
Type of soil	Original state	Frozen state	Thawed state
Dense soils			
Loose soils			

Figure 4.6 Volumetric Change of Dense and Loose Soil in Freezing-thawing Cycles

The volume change for loose soils is going down together with freezing-thawing cycles until to a residual value, while it is going up together with freezing-thawing cycles until reaching a residual value for dense soils. The tendency of these two kinds of soils is shown in Figure 4.7. These volumetric behaviors are seen to be irreversible and considered as plastic in the model.

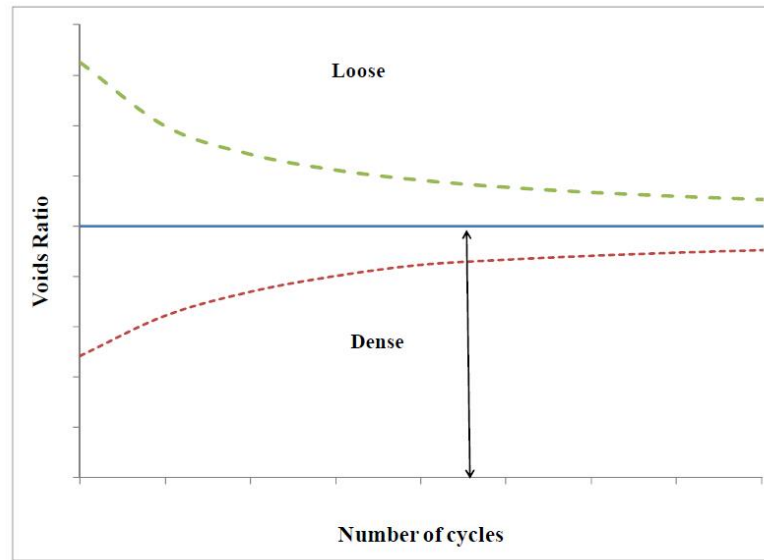


Figure 4.7 Behavior of Dense and Loose Soil in Freezing-thawing Cycles

How to classify dense soil and loose soil is based on the relationship between pre-consolidation pressure and the current stress state. There is a ratio p/p_0 , which is the net stress now over the current pre-consolidation pressure. This ratio generally describes the openness of soil structure, and dense soil will have a low ratio while a loose soil will have a high ratio.

The volume increment of soil sample during the freezing process will decrease the elastic domain of the soil, and as a result of this, the LC curve will move to the left. Consequently, P_0 value will decrease in freezing process. As for thawing process, elastic domain will increase because of the decreasing of volume, and LC curve will move to right side. Consequently, P_0 value will increase. The moving of LC curve during cyclic freezing-thawing process is shown in Figure 4.8.

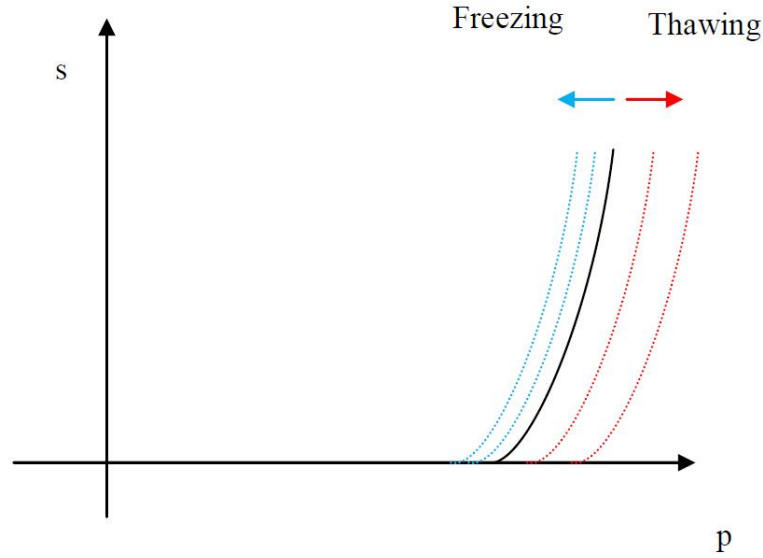


Figure 4.8 LC Curve Movements during Freezing and Thawing

Then plastic strain due to ice formation will also be taken into consideration, and it is related to the expansion and contraction because of freezing and thawing. Then an interaction function related elastic strain and plastic strain because of ice formation will be stated in Eq. 4.5 as follows.

$$f = \frac{\dot{\epsilon}_{vi}^p}{\dot{\epsilon}_{vi}^e} \quad (4.5)$$

With the interaction function, freezing and thawing interaction curves will be discussed separately. In terms of freezing process, phase change from water to ice will cause negative elastic strain which shows in expansion, and the plastic because of ice formation is also negative, as a result of which, the function f is positive. Figure 4.9 below shows the interaction curve during freezing of dense soil as well as loose soil.

During freezing, p/p_0 will increase because of the decreasing of p_0 value, and dense soil has a capacity to accumulate larger plastic strain than loose soil, so dense soil starts from 1 to 2, while loose soil starts from 3 to 4.

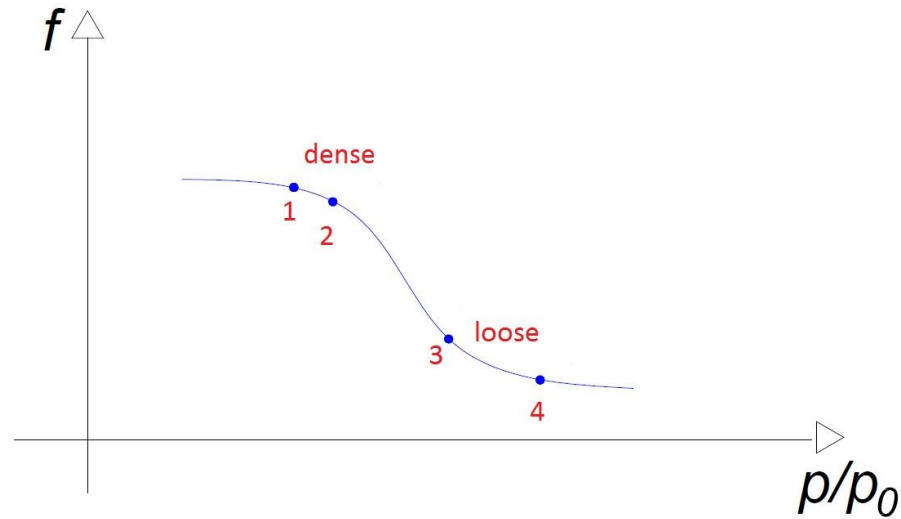


Figure 4.9 Freezing Interaction Curve

In terms of thawing process, the function f is still positive for both of strains are positive. Figure 4.10 shows the interaction curve during thawing process of dense soil as well as loose soil. During thawing, p/p_0 will decrease because of the increasing of p_0 value, and loose soil will have the capacity to accumulate more plastic strain, so loose soil starts from 5 to 6, while dense soil starts from 7 to 8.

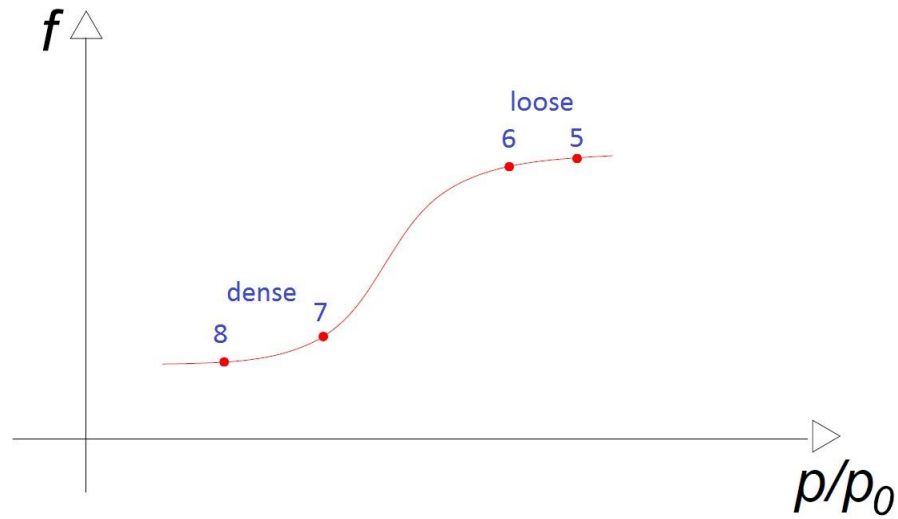


Figure 4.10 Thawing Interaction Curve

These two interaction curve can be combined together in Figure 4.11. During freezing, the total amount of plastic strain can be obtained by summing the plastic strain calculated by tracing the freezing interaction function. During thawing, how to get total plastic strain is a similar process. Therefore, the total amount of plastic strains is the summation of the plastic strains which accumulate during freezing and thawing. When the amount of negative plastic strains occurring during the freezing is equal to the amount of positive plastic strain which occur during thawing, then a residual state is reached. As shown in Figure 4.11 below, the point 'E' is the equilibrium point, which is the intersection of the two interaction curves.

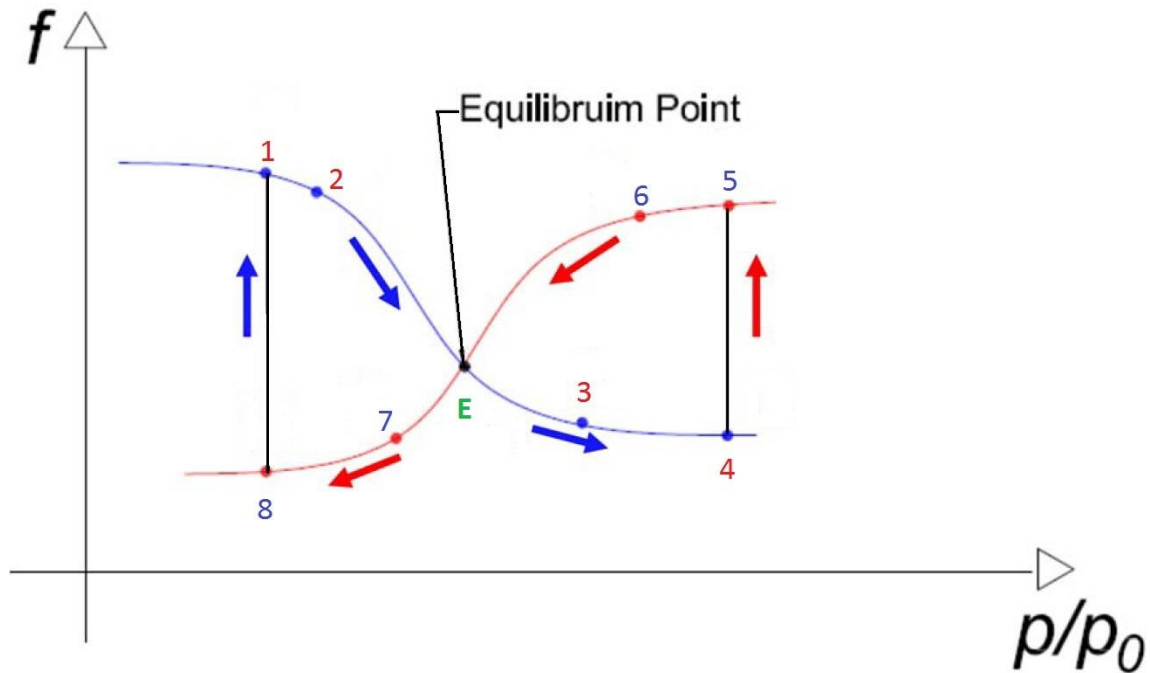


Figure 4.11 Freezing-thawing Interaction Curve

4.4 Comparison cases between modeling and experimental results

This part will compare results obtained from tests to results from the model we develop. Since modeling is a long run task, more tests with different conditions still need to be conducted, and many parameters still need to be adjusted to make the preliminary model more accurate and comprehensive. In comparison part, the thesis will show several test cases where the mechanical behavior of soil samples during cyclic freezing-thawing are simulated by the model well. Also, this part will give an example that the mechanical behavior is not well simulated by the model.

All the cases in modeling will share the same soil parameters shown in Table 4.1, and the same interaction function parameters shown in Table 4.2

Table 4.1 Soil Parameters

λ_0	0.13
κ	0.02
β	1.4
r	0.75
I (J/kg)	334000
P_c (Mpa)	0.01
α	-3

Table 4.2 Interaction Function Parameters

ffreezing1	1.3
ffreezing2	-0.23
ffreezing3	10
ffreezing4	0.1
fthawing1	1.1
fthawing2	0.23
fthawing3	10
fthawing4	0.1

Case 1: 10kpa-Cycling

In this case, soil is normally consolidated with a pre-consolidation pressure of 10kpa. After consolidation under 10kpa, soil sample will be subjected to cyclic freezing-thawing process. The cyclic part in consolidation curve from test will be denoted in Figure 4.12 a); cyclic freezing-thawing curve from test results is shown in Figure 4.12 b); interaction curve during this process is shown in Figure 4.12 c); comparison between test and model results in void ratio versus number of cycles is shown in Figure 4.12 d).

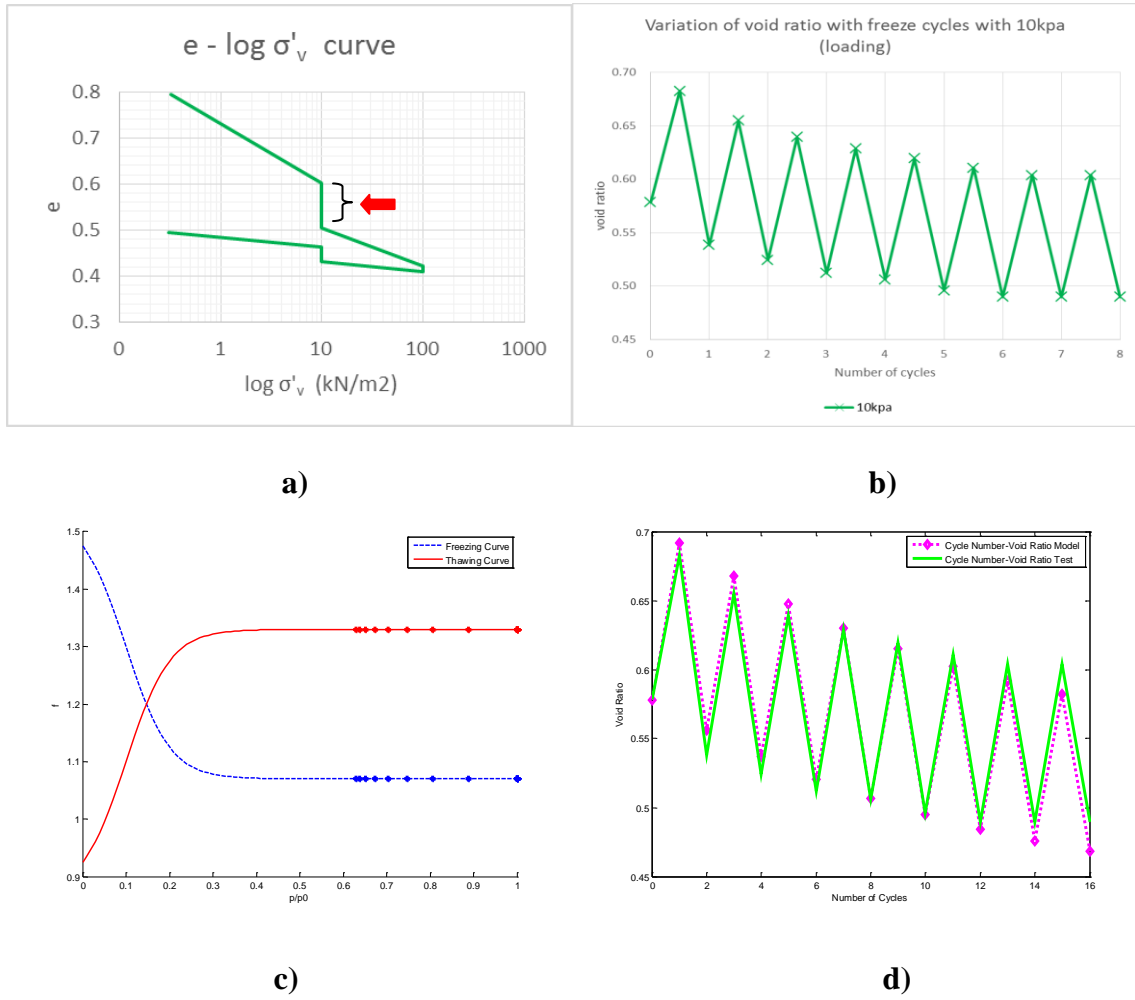


Figure 4.12 Interaction Curve and Comparison Results 1 a) Consolidation Curve b) Cyclic Freezing-thawing Curve c) Interaction Curve d) Results Comparison

It can be observed from the figure that soil sample shows a behavior of compaction, and void ratio reduced during cyclic freezing-thawing process. For it is normally consolidated, the starting p/p_0 value is 1. From the interaction curve, we can also conclude that the soil is loose for the points are on the right side (loose soil). The plastic strain due to thawing is higher than that due to freezing, so the soil should show a behavior of compaction, which is going down as in Figure 4.12 d).

Case 2: 100kpa-Cycling

In this case, soil is normally consolidated with a pre-consolidation pressure of 100kpa. After consolidation, soil sample will be subjected to cyclic freezing-thawing process. The cyclic part in consolidation curve from test will be denoted in Figure 4.13 a); cyclic freezing-thawing curve from test results is shown in Figure 4.13 b); interaction curve during this process is shown in Figure 4.13 c); comparison between test and model results in void ratio versus number of cycles is shown in Figure 4.13 d).

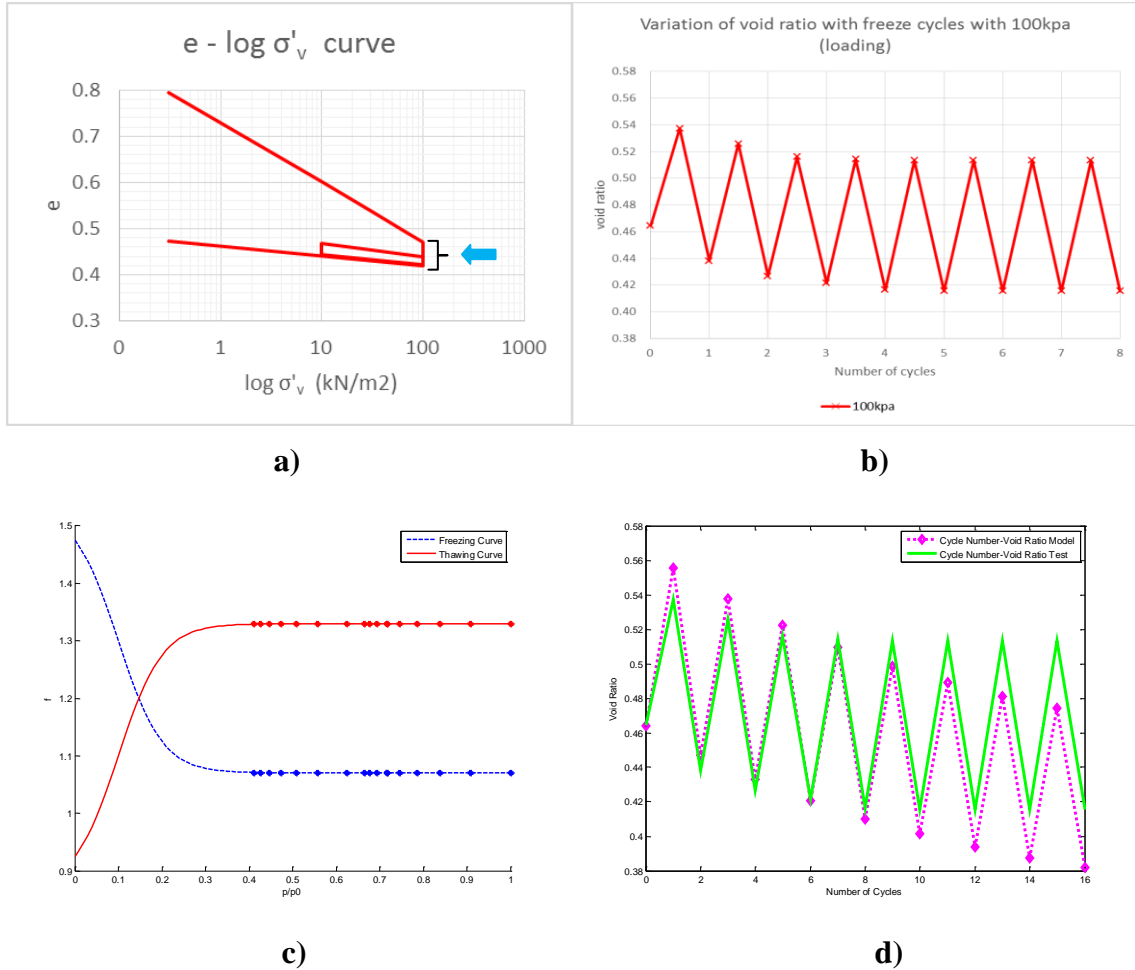


Figure 4.13 Interaction Curve and Comparison Results 2 a) Consolidation Curve b) Cyclic Freezing-thawing Curve c) Interaction Curve d) Results Comparison

It can be observed from the figure that soil sample shows a behavior of compaction, and void ratio decreases during cyclic freezing-thawing process. Ratio p/p_0 will decrease gradually until finally reach the equilibrium point, where the volumetric behavior of soil sample will be stable. When compared with Case 1, the range of volume changes in Case 2 is smaller than that in Case 1. This is because Case 2 is under a higher loading. The difference is also demonstrated by the model. The simulation of model in this case is not working well.

Case 3: 1250kpa-10kpa-Cycling

In this case, soil is over consolidated with a high pre-consolidation pressure of 1250kpa. Freezing-thawing cycles are under an unloading pressure of 10kpa. The cyclic part in consolidation curve from test will be denoted in Figure 4.14 a); cyclic freezing-thawing curve from test results is shown in Figure 4.14 b); interaction curve during this process is shown in Figure 4.14 c); comparison between test and model results in void ratio versus number of cycles is shown in Figure 4.14 d).

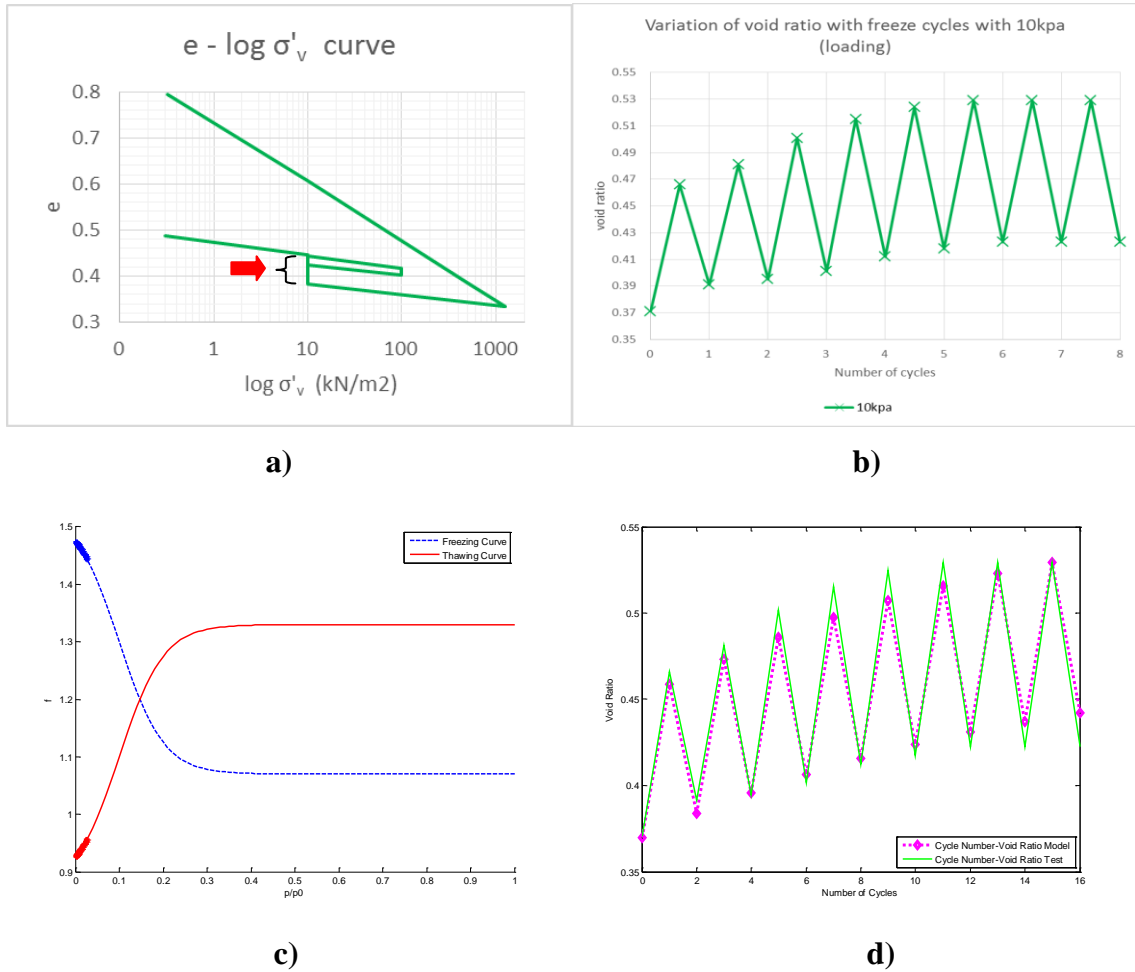


Figure 4.14 Interaction Curve and Comparison Results 3 a) Consolidation Curve b) Cyclic Freezing-thawing Curve c) Interaction Curve d) Results Comparison

It can be observed from the figure that soil sample shows a behavior of expansion, and void ratio increase during cyclic freezing-thawing process. This is reasonable, for soil is over consolidated; the ratio p/p_0 at the beginning is on the left side of interaction curve (dense soil). Plastic strain due to freezing is larger than that due to thawing, so it shows a behavior of expansion, as in Figure 4.14 d). Ratio p/p_0 will

increase gradually until finally the equilibrium point is reached, where the volumetric behavior of soil sample will be stable. This process is to the opposite of Case 1 and 2.

Case 4: 1250kpa-100kpa-Cycling

In this case, soil is over consolidated with a high pre-consolidation pressure of 1250kpa. Freezing-thawing cycles are under an unloading pressure of 100kpa. The cyclic part in consolidation curve from test will be denoted in Figure 4.15 a); cyclic freezing-thawing curve from test results is shown in Figure 4.15 b); interaction curve during this process is shown in Figure 4.15 c); comparison between test and model results in void ratio versus number of cycles is shown in Figure 4.15 d).

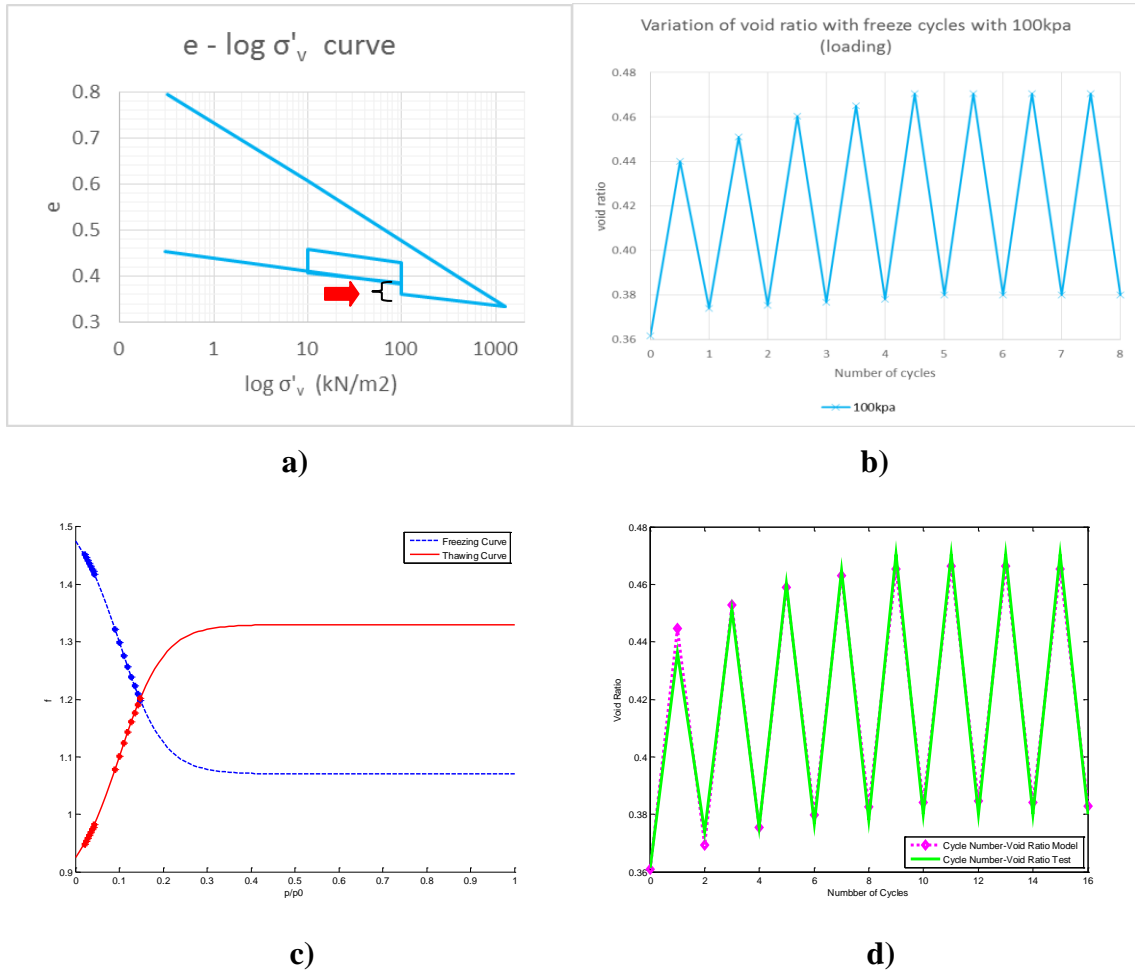


Figure 4.15 Interaction Curve and Comparison Results 4 a) Consolidation Curve b) Cyclic Freezing-thawing Curve c) Interaction Curve d) Results Comparison

It can be observed from the figure that soil sample shows a behavior of expansion, and void ratio increases during cyclic freezing-thawing process. Ratio p/p_0 will increase gradually until finally reach the equilibrium point, where the volumetric behavior of soil sample will be stable. Case 4 looks more stable when compared with Case 3, as shown in Figure 4.15 d). Void ratio keeps stable around 8 cycles, where the equilibrium point is also reached in the interaction curve. Besides, the range of volume

change in Case 3 is larger than in Case 4, for they share the same pre-consolidation pressure but Case 4 is under a higher loading. The model also demonstrates this point.

Case 5: 500kpa-10kpa-Cycling-100kpa-Cycling

In this case, soil is over consolidated with a pre-consolidation pressure of 500kpa. Sample is unloaded to 10kpa, and the following load steps are the same as stated in Section 4. Cyclic freezing-thawing results from test results are shown in Figure 4.16 b); interaction curve during this process is shown in Figure 4.16 c); comparison between test and model results in void ratio versus number of cycles is shown in Figure 4.16 d).

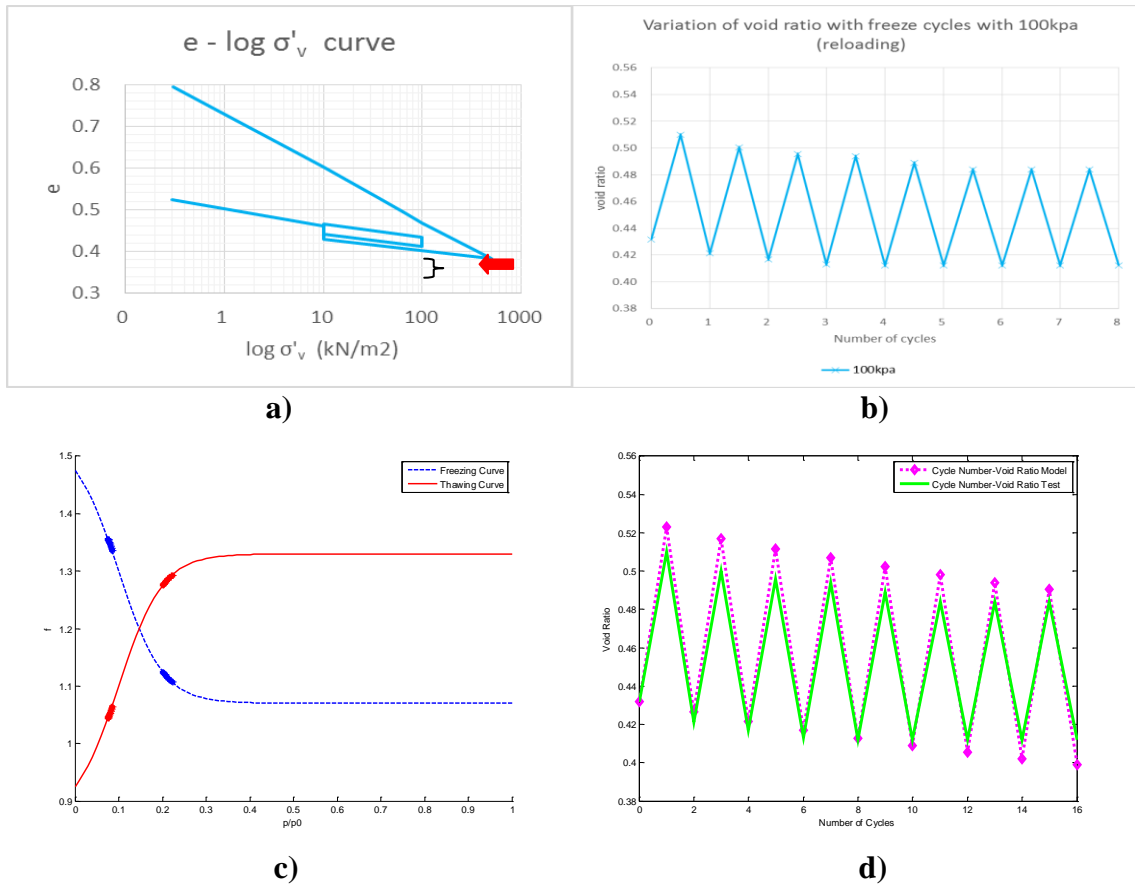


Figure 4.16 Interaction Curve and Comparison Results 5 a) Consolidation Curve b) Cyclic Freezing-thawing Curve c) Interaction Curve d) Results Comparison

It can be observed from the figure above that the soil sample shows a behavior of compaction, and void ratio reduced during cyclic freezing-thawing process. The model simulated the volumetric behavior of soil sample well though the model results are still not stable. In order to know in this situation whether the points on interaction curve will convergent to the equilibrium point as we clarified in the former part, we tried more cycles to show the development, as shown in Figure 4.17. When volume change is more stable (more cycles), the points on interaction curves will be more near the equilibrium point, which demonstrate our illustration about the model in the former part is reasonable.

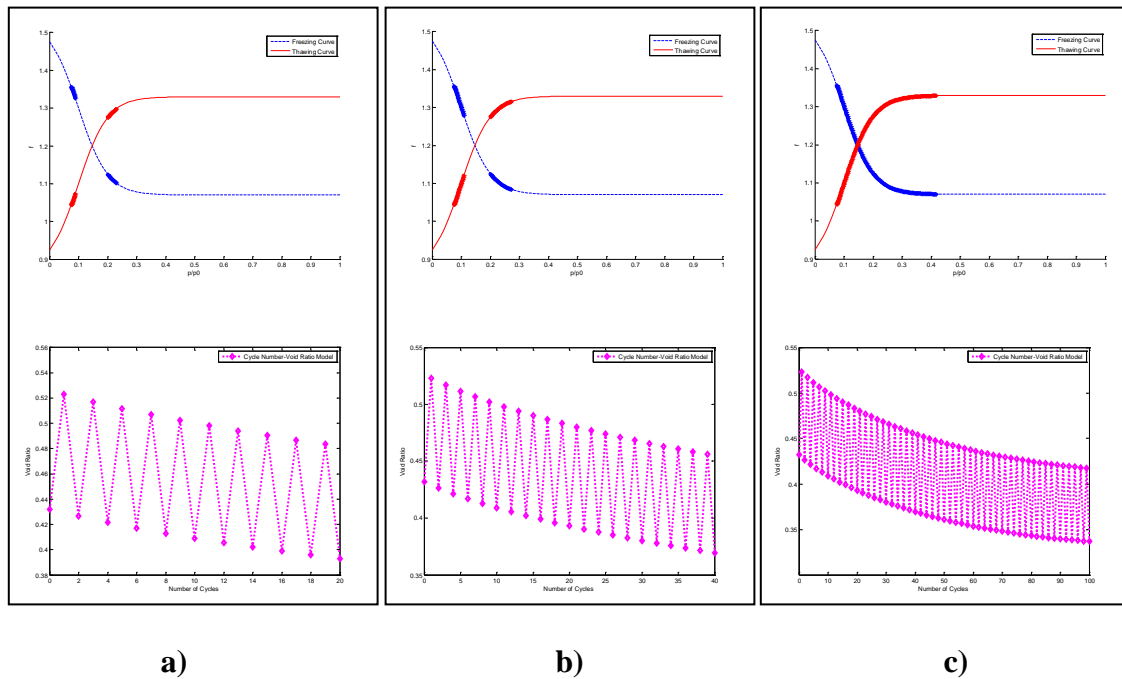


Figure 4.17 Development of Interaction Curve with Cycle Number a) 10 Cycles b) 20 Cycles c) 50 Cycles

Case 6: 500kpa-100kpa-Cycling-10kpa-Cycling-100kpa-Cycling

In this case, soil is over consolidated with a pre-consolidation pressure of 500kpa. Then it will be subjected to a series of loading and unloading steps as well as freezing-thawing cycles after each corresponding load steps, as shown above. The cyclic part in consolidation curve from test will be denoted in Figure 4.18 a); cyclic freezing-thawing curve from test results is shown in Figure 4.18 b); interaction curve during this process is shown in Figure 4.18 c); comparison between test and model results in void ratio versus number of cycles is shown in Figure 4.18 d).

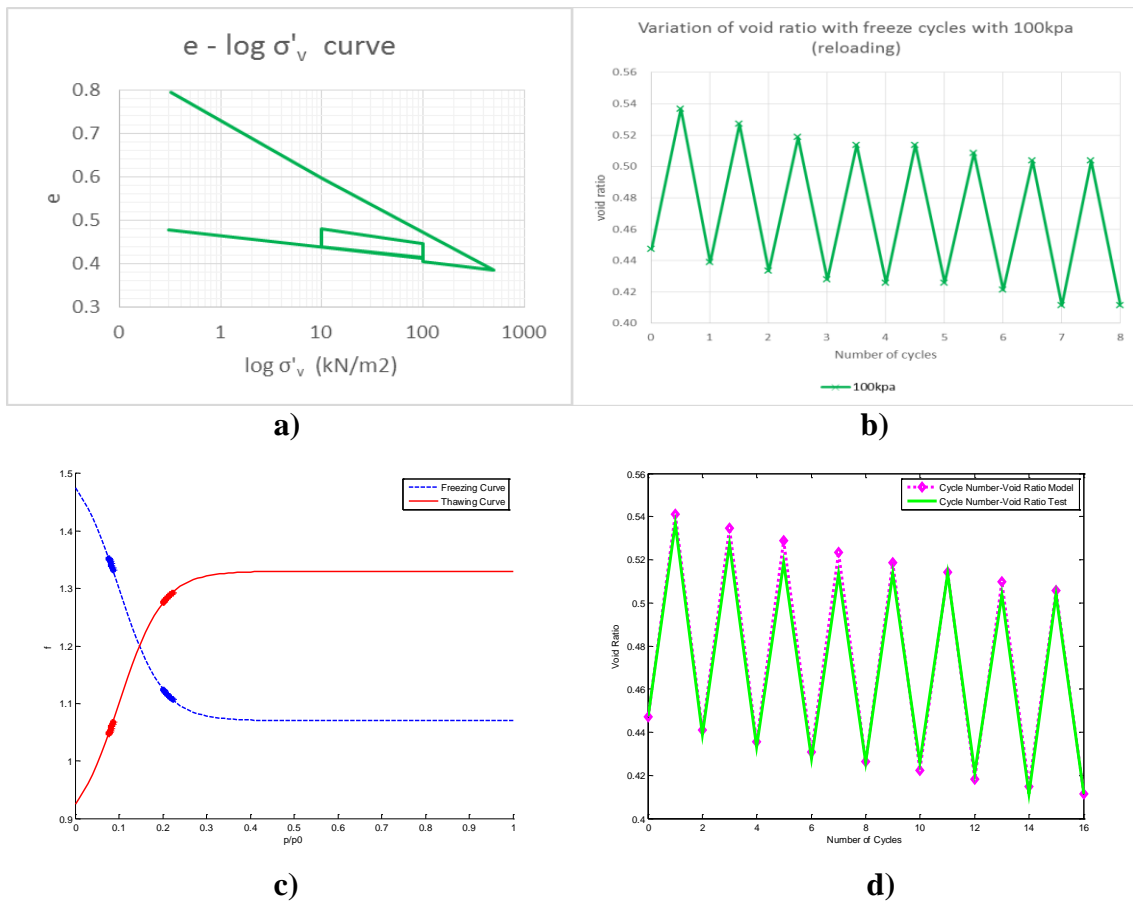


Figure 4.18 Interaction Curve and Comparison Results 6 a) Consolidation Curve b) Cyclic Freezing-thawing Curve c) Interaction Curve d) Results Comparison

It can be observed from the figure that soil sample shows a behavior of compaction, and void ratio reduced during cyclic freezing-thawing process. Interaction curve also behaves similarly as case 5.

Many more cases are also simulated by the model; some works well, some still need to be modified a little bit, as Case 2. All the cases demonstrate the mechanical model introduced in this thesis is reasonable and feasible. However, many aspects are still need to be improved, one of which is how to make the results from model as stable as those from tests after given cyclic freezing-thawing cycles. In order to make the model more effective and accurate, more tests with different conditions still need to be conducted, and many parameters still need to be adjusted, which will be illustrated in future work in Section 5.

5 SUMMARY AND FUTURE WORK

5.1 Summery

In this research, a series of cyclic freezing-thawing tests under different loading conditions have been conducted, and a mechanical model to simulate volumetric behavior during cyclic freezing-thawing has been developed. The achievements of this research work are as follows:

- A better understanding on the behavior of soils subjected to F-T cycles has been gained in this research.
- A new set of high quality experimental data of cyclic freezing-thawing soils under different loading conditions and different cyclic freezing-thawing history has been obtained.
- It was observed that loose soil samples show a behavior of contraction, while dense soil samples show an opposite behavior.
- An advanced mechanical model has been developed to simulate the volumetric behavior of soils subjected to cyclic freezing-thawing cycles.
- The model has been able to capture the main tendencies observed in the experiments.

All these achievements in the research topic give the credit to:

- Selecting proper soil type and experimental devices for tests.
- Choosing proper water content and following standard test procedures.
- Incorporating the three phase conditions of frozen soil (i.e. unfrozen water, solid and ice) in a consistent mathematical framework.
- Extending generalized constitutive laws to account for cyclic freezing-thawing soil behavior.
- Selecting reasonable equations and soil parameters for calculation and simulation.
- Demonstrating the application of the preliminary model developed by cases comparisons between experimental results and modeling results.

5.2 Scope for future work

The achieving of goals in this research fill the gaps existed in frozen soil research to some extent. However, more work are still in great need of to modify and develop the mechanical model in this thesis, so as to make the model more accurate, comprehensive and hold a wider application range. These future works will be grouped to two aspects, experimental campaign and modeling campaign, which will be clarified as follows:

As for test campaign, a series of complementary tests should be conducted:

- Similar tests with different temperature ranges (e.g. $-20^{\circ}\text{C} \sim 5^{\circ}\text{C}$).
- Creep tests under given subzero temperatures with different pre-consolidation pressures (e.g. Normally consolidated, Lightly over consolidated, and Highly over consolidated).
- Similar creep tests after cyclic freezing-thawing cycles.
- Consolidation tests at different subzero temperatures.
- Similar tests with different soil types (e.g. Kaolin), different initial conditions (e.g. water content, void ratio)

As for modeling part, many more factors will also be taken into consideration:

- Deformation of soil particles resulting from temperature changes.
- Deformation due to cryogenic suction.
- Volumetric behaviors under the influences of soil creep.
- Hydraulic behavior of cyclic freezing-thawing frozen soils.
- Make more adjustment and modification on the interaction curve parameters.

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APPENDIX A

The appendix lists equations of all the basic models incorporated in this thesis.

A.1 Tice Model

Tice model (Tice et al., 1976) is referred to in this thesis for the calculation of saturation degree of ice. The function relates saturation degree of ice with temperature as well as an experimental factor α .

$$S_i = \begin{cases} 1 - [1 - (T - T_0)]^\alpha & T \leq T_0 \\ 0 & T > T_0 \end{cases} \quad (\text{A1})$$

Where T is temperature in Celsius temperature; T_0 is freezing temperature of pore water in Celsius temperature; α is an experimental factor.

A. 2 Clausius–Clapeyron Equation

The equilibrium between liquid water and ice phases is described by the Clausius–Clapeyron equation. This equation represents a thermodynamic requirement for equilibrium that needs to be satisfied by P_i , P_l and T .

$$P_i = \frac{\rho_i}{\rho_l} P_l - \rho_i l \ln \left(\frac{T}{273.15} \right) \quad (\text{A2})$$

Where P_i and P_l are pressure of ice and pressure of unfrozen water; ρ_i and ρ_l are density of ice and water; l is the latent heat of fusion; T is temperature in Celsius temperature.

In this thesis, this equation will be used to calculate the pressure of ice together with Cryogenic Suction formulation as well as equation by Thomas et al., 2009.

$$S_c = \rho_l \times l \times \ln\left(\frac{T}{T_0}\right) \quad (\text{A3})$$

Where S_c is Cryogenic Suction; l is the latent heat of fusion; ρ_l is the density of water.

A. 3 Mechanical Constitutive Model

The mechanical constitutive model used in the mechanical modeling part is modified Barcelona Basic Model (BBM). As elaborated in Section 4, BBM is a constitutive for unsaturated soils. When it is extended to frozen soils, the two variables, net stress and cryogenic suction, are defined as follows.

$$\sigma_n = \sigma - \max(P_i, P_l, 0) \quad (\text{A4})$$

$$S_c = \max(P_i - P_l, 0)$$

Where σ is the mean stress; σ_n is the net stress.

The Load-Collapse (LC) curve (shown in Figure A1), which causes the yielding of the soil. The yield mean stress on LC curve is calculated by:

$$p_0 = p^c \left(\frac{p_0^*}{p^c} \right)^{\frac{\lambda_0 - \kappa}{\lambda_s - \kappa}} \quad (\text{A5})$$

Where,

$$\lambda_s = \lambda_0 [r + (1 - r) \exp(-\beta s)] \quad (\text{A6})$$

p_0 is mean yield stress; r and β are model parameters; λ_s is slope of consolidation under cryogenic suction s ; λ_0 is slope of consolidation curve when cryogenic suction value is 0.

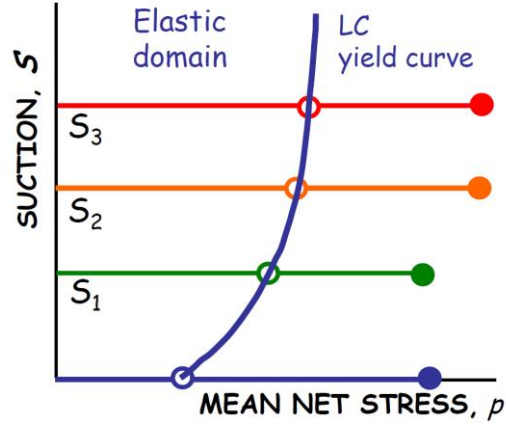


Figure A1 LC Curve of BBM

As for hardening law in BBM, the change of pre-consolidation pressure is calculated by:

$$dp_0^* = \frac{1+e}{\lambda_0 - \kappa} \times p_0^* \times d\varepsilon_v^p \quad (A7)$$

Where λ_0 is slope of virgin consolidation curve when cryogenic suction is 0; κ is slope unloading or reloading curve; e is void ratio; the plastic volume strain because of ice can be calculated by interaction function multiplied by elastic volume strain as introduced in Section 4.

A.4 Interaction Functions for Double Structure Model

In this thesis, interaction function derived from double structure plasticity model (Sanchez et al., 2005) will be incorporated to help make clear the relationship of elastic volume strain and plastic volume strain due to ice formation. Freezing interaction

function and thawing interaction function will be used separately in freezing and thawing process.

$$f_{freezing} = ff1 + ff2 \times \tanh(ff3 \times (p / p_0) - ff4) \quad (A8)$$

Where ff1, ff2, ff3, and ff4 are parameters for freezing function; p/p0 is the ratio describing the openness of soil structure as introduced in Section 4.

$$f_{thawing} = ft1 + ft2 \times \tanh(ft3 \times (p / p_0) - ft4) \quad (A9)$$

Where ft1, ft2, ft3, and ft4 are parameters for freezing function; p/p0 is the ratio describing the openness of soil structure as introduced in Section 4.